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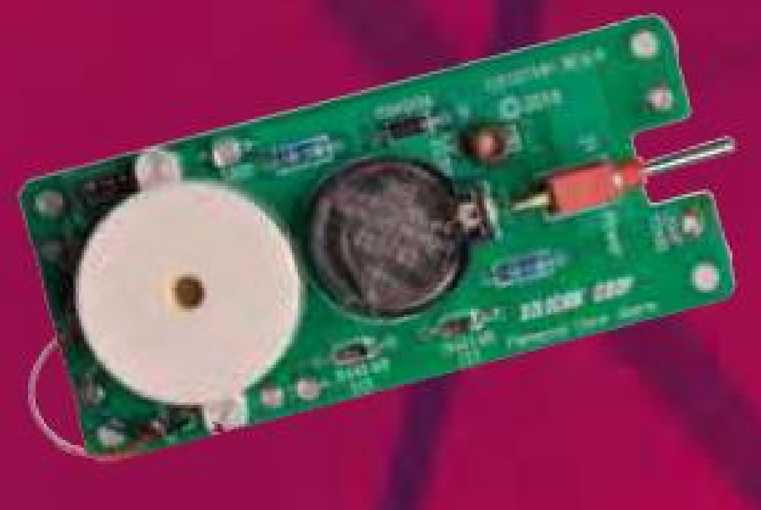

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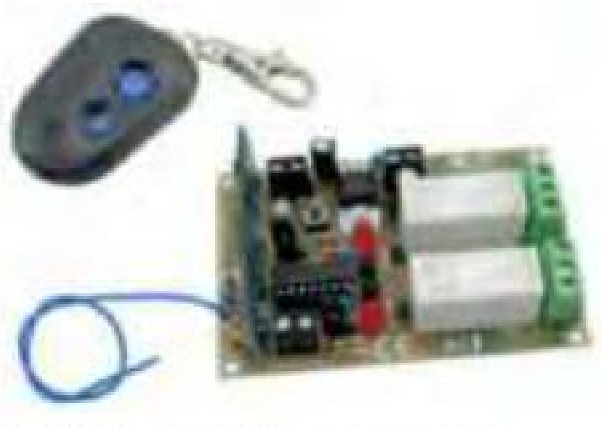

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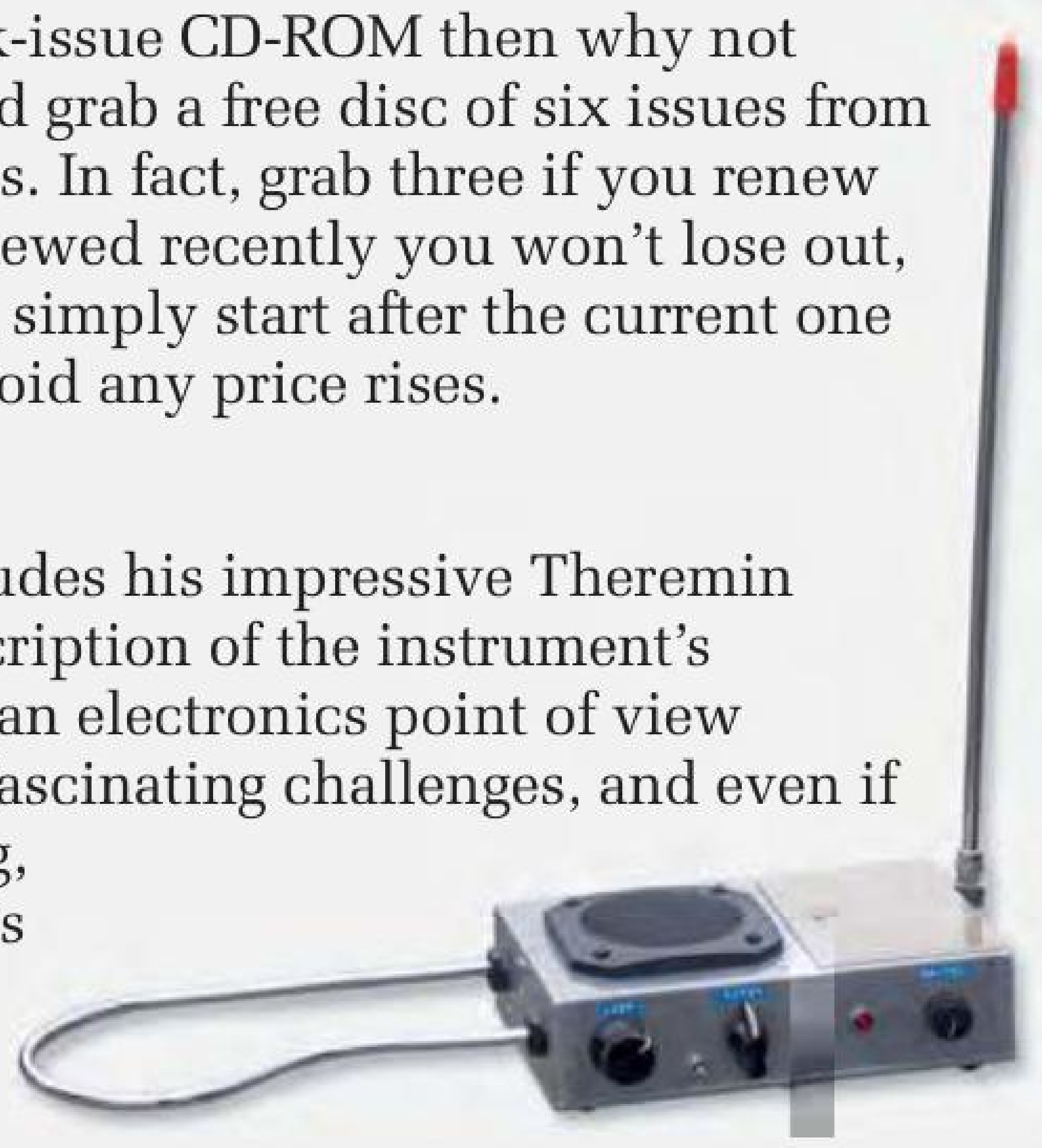
The PE Theremin

In this issue Jake Rothman concludes his impressive Theremin series with a comprehensive description of the instrument's volume and VCA sections. From an electronics point of view Theremin design presents some fascinating challenges, and even if electronic music is not your thing, I recommend Jake's writing for his practical and perceptive take on advanced analogue design.



One more point relating to this month's *Audio Out* – we know that some parts in our projects can be hard to source and Jake has put together a little pack of parts that might otherwise take a fair bit of hunting down. We don't have any plans to become a comprehensive parts shop – do please use our loyal advertisers for that – but where we can help you pick up a few key parts we'll attempt to do so.

PIC n' Mix

Life has a way of upsetting the most carefully thought out plans and I'm sorry to report the Mike Hibbett needs to take a short sabbatical from *PE*. He aims to be back later in the year and will 'pop in' with a couple of articles before he returns properly. The very good news is that Mike has assured me that in the long term he is 100% committed to *PE*, and even suggested that he has so many ideas that readers might get tired of hearing from him. I explained, in the nicest way, that he was talking nonsense and we really do look forward to very many more articles from him. We wish him and his family all the best.

Matt Pulzer
Publisher

5G primer

Offering much more than a simple 3G-to-4G-style rise in speed – moving to 5G promises a true break from wired technologies dating back to the Victorian era. Barry Fox assesses the challenges and opportunities.

The UK now has 5G – courtesy of network EE, formerly Orange and T-Mobile, now part of the BT Group, and promoted by the some-may-find-somewhat-irritating actor, Kevin Bacon. The new service is being sold with the simple tag line – 'a more reliable connection in busy places'.

The need for a simple tag is understandable. Many mobile users are still struggling to find a reliable 4G connection and will pay for 5G if they think they are buying a better service. But 5G is actually about much more than this. The BBC, for instance, is already testing 5G as a carrier link for outside broadcast cameras, and to deliver live radio broadcasts to the Orkneys as an alternative to more conventional terrestrial transmissions.

What's the big deal?

Promoting 5G's less-than-simple features with hard facts will take time, so *PE* readers may appreciate a brief run-down of what 5G brings to the telecoms table. This may also help understand why Western security services are worried about buying 5G from Chinese company Huawei.

In a nutshell, 5G could be the first real opportunity for the world to kiss goodbye to the Victorian practice of digging up roads, pavements and fields to lay copper and fibre cables, and then drilling holes through walls and nailing wires around door frames for reliable home or office networks.

5G is the first radio system designed from the ground up to support any available spectrum, between 400MHz and 90GHz. The main 5G spectrum is global, so equipment works worldwide. Low bands, below 6GHz, offer wide cover, with better outdoor-to-indoor penetration – but *relatively* slow speeds. Millimetre-wave spectrum (from 24-28GHz and 39GHz) gives shorter range cover, with higher speeds, so will be used for local 'hot spots', both indoors for home networking and outdoors with transceivers on street furniture (lamp posts). 5G can also be used on unlicensed spectrum around 5GHz. All the frequencies can be used together so that equipment searches for the best options available.

Gigabits per second

Finnish company Nokia, which moved from making paper to AV to phones, and is now a 5G network design leader, predicts 5G will deliver speeds of 100Mbps whenever needed, with these routine rates rising to 1Gbps, and peak rates of 10Gbps – compared to 10Mbps for many existing wired broadband connections. Nokia believes 5G speeds will eventually reach 20Gbps.

Samsung recently announced a 5G chipset, code-named 'Balong', which delivers speeds up to 4.6Gbps for the sub-6GHz bands, with 6.5Gbps in the millimetre high-frequency bands. This is already 10 times faster than anything 4G can achieve.

The techniques 5G relies on to modulate the radio carrier wave, and push ever closer to the brick-wall capacity limits defined by Claude Shannon of Bell Labs in 1948, include the use of OFDM (orthogonal frequency-division multiplexing) to spread data across separate narrowband channels at different frequencies, already the basis of digital radio and TV broadcasting; 256 QAM (quadrature amplitude modulation), which offers 256 code combinations from eight-bit symbols; and LDPC (low-density parity-check) for robust error correction.

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Lorenz

Cities are topographically dynamic – skylines, building materials, shapes and surfaces are continually changing. This matters for 5G because their millimetre-wave signals are optimally supplied on a line-of-sight basis and rapidly attenuate when faced with physical obstructions. Shown here, the building work that forced the author to abandon wireless broadband and return to a wired service provider – but in the future, 5G promises MIMO aerials to steer the signal.

The demands of ever-higher frequencies

Higher frequencies need focussed beaming in chosen directions, which is why microwave and satellite systems use big dishes – but 5G has to work without dishes. The enabling technology is called MIMO (multiple-input multiple-output), and it builds on the principles used for flat satellite aerials, like BSB's ill-fated 'Squarial'. The phases of signals sent to a 'chessboard' of transceiver cells are juggled to concentrate a wireless beam and steer it horizontally and vertically. This increases the antenna gain and helps compensate for signal loss caused by the atmosphere at higher frequencies. The challenge is to make the MIMO antennae smaller, by using chip fabrication techniques. They are already down to 10mm square, and sure to get smaller.

Low latency

5G has also been designed from the ground up to offer low latency, which means a reduction in the time it takes for a local device to send data to a remote system, and receive back a reliable response. Latency encourages on-line gamers to over-steer, like novice boaters.

Current network lags are around 20ms or more; 5G promises around 1ms. This means that home equipment can be cheap and dumb, with less computer processing inside the box, and the intelligence needed to do clever things, mainly in a remote control centre. We are already seeing this with voice control systems such as Alexa, which 5G should make faster and smarter.

Low latency has been driven by the automotive industry which needs it for braking autonomous (self-driving) vehicles, so that cars stop at a red light, and by the medical profession, which wants a doctor in one continent to remote-control operating table scalpels in another.

Perhaps the biggest difference between 4G and 5G is that whereas with 4G everyone gets the same service, 5G lets the operator 'slice' the network into virtual networks which offer different configurations, some with low latency and less congestion. Those who pay more will get greater reliability.

The bedrock industry standard for 5G is called 5G NR, for 'New Radio'. Release 15 was agreed in late 2017 by 3GPP, the 3rd Generation Partnership Project, which is supported by all the major telecommunications standard-setting organisations. Release 16 is due this year and Release 17 due in 2020. But these deal only with 'enhancements'; the basic essentials are now solid. This is how EE can safely sell 5G.

Real-world operation

Only time will tell how MIMO copes with delivering 5G to cars in areas as diverse as crowded high-rise cities, rustic roads and in deep signal-blocking valleys in Wales and Scotland. In cities, new and taller buildings continually rise to block, or spuriously reflect, wireless signals. In theory, 5G with MIMO antennae should be able to steer wireless signals past tall buildings. But in practice? An example may help here.

When I ditched BT as my fixed-line supplier because of price hikes, I tried the 4G Relish fixed-wireless broadband service. The easily available free tools like Ookla Speedtest (**www.speedtest.net**) showed speeds were initially healthy at well over 10Mbps and sometimes close to 20Mbps. But then speeds dropped dramatically to a very few Mbps for downloading, with latency of hundreds of milliseconds and unmeasurably slow upload speeds. The service collapse followed erection of a large new building nearby, clad with signal-blocking/reflecting metal scaffolding. Relish ran checks that showed subscribers' broadband receivers were locking on to the wrong transmitter tower.

The first site builder went bust and a new one ceased meaningful work. So the Relish signal has for more than a year remained unusable. Relish decently cancelled my contract and I went back to a wired broadband connection. A senior spokesman for the local council (Camden, in London) seemed worryingly incapable of understanding even the basic difference between wired and wireless, assuring that 'Virgin Media… provide much of the broadband in the area…. through a coaxial cable directly to each property which provides both broadband, TV and phone line services (and) these would not be affected by the metal scaffolding.'

MIMO won't fix the kind of technical ignorance that pervades politics, but it might well fix the practical problems which ignorance exacerbates.

Cosmic radio cracked

Techno Talk

Mark Nelson

Here's some heavenly news: scientists are getting close to finding an explanation of one of the strangest radio phenomena of the cosmos. You can read about it below, along with earlier attitudes to extra-terrestrial communication, plus some practical experiments that you might care to attempt.

Fast radio bursts (FRBs) were one of the topics discussed in *Techno Talk* for June 2017. At that time, the origin of these mysterious radio signals from galaxies deep in outer space was highly controversial, with scientists from Harvard University suspecting they might be caused by a species of super-advanced aliens firing up their interstellar spacecraft. Two years on, researchers are getting closer to a plausible explanation. Someone well placed to sum up current thinking is Brian Metzger, an astrophysicist and associate professor at Columbia University, New York. Last year, he won the New Horizons in Physics Breakthrough Prize, and in March of this year he and two colleagues circulated a paper in which they argued that FRBs arise from synchrotron maser emission from ultra-relativistic magnetised shocks, such as produced by flare ejecta from young magnetars.

incidentally, that word 'maser' gave me a jolt – maybe you too? The maser was the forerunner of the laser; and, in my ignorance, I had assumed that masers were obsolete nowadays, but evidently not. Lasers and masers do of course work on similar principles, with lasers generating light and masers producing energy at microwave radio and infrared frequencies.

Back to magnetars – they are a type of neutron star believed to have an extremely powerful magnetic field. Although their diameter is only around 20km (12 miles), their mass is two to three times that of the Sun, meaning that a tablespoon of magnetar would have a mass of over 100 million tons. They spin extremely rapidly, rotating in less than a second, with their intense magnetic field giving rise to very strong and characteristic bursts of X-rays and gamma rays that create shock waves that in turn beam a short, laser-like flash of radio waves halfway across the universe.

All of this is definitely powerful stuff. Of course, there is only room for a summary here, but you can read plenty more at: **http://bit.ly/pe-aug19-tt1**

Practical electronics

Feeling inspired to do some cosmic radio research of your own? Many FRBs have been recorded at radio frequencies (around 1400MHz), with a few detected at lower frequencies in the low UHF range of 400-800MHz (within the coverage range of some scanner radios). Unfortunately, you would need an antenna set-up substantially larger than Jodrell Bank, although the team there is devising a way of linking a number of UK-based radio telescopes (collectively known as the eMERLIN interferometer) to create a far larger 'virtual' antenna.

The good news is that there are plenty of other kinds of radio astronomy that you can carry out at home, with good results. The September 2010 issue of this magazine included an admirable project for constructing a low-cost, compact and easy-to-build *Planet Jupiter Receiver* for hearing radio signals from the gas giant. Simple and compact antennas can be used and software-defined radio (SDR) receivers are becoming a popular choice. For detailed information I would refer you to two excellent articles published recently in a magazine that, like this one, traces its lineage to the *Practical Wireless* family. Its name is *Radio User* and the articles are: *Receiving Signals from Space* (May 2019) and *Using SDR for Amateur Radio Astronomy* (April 2019). Both are recommended and available at: **http://bit.ly/pe-aug19-tt2**

Mars mania

It might surprise you to know that fascination with extra-terrestrial radio communication is far from new. Already in 1896 Nikola Tesla expressed the view that radio might be powerful enough to establish contact with beings on the planet Mars. He and others detected unexpected radio signals that they thought came from a neighbouring planet (we now know that these were the Earth's ionospheric radiation).

Guglielmo Marconi renewed interest in January 1920, when he told the *Daily Mail* newspaper that he was investigating the origin of mysterious signals that he had recently received on his wireless instruments. 'Nobody can yet say definitely whether they originate on the earth or in other worlds.' Two years later, in June 1922, he crossed the Atlantic aboard his radio research ship, the *Elettra*. It was widely reported that he was hoping to tune into Mars, although on arrival in New York he declared that any suggestions of interplanetary communication were 'absurd' and 'ridiculous', Nevertheless, he asserted that the (extraordinary) 150,000m wave which he had picked up in the Mediterranean several months earlier certainly did not originate on the earth. You can see his apparatus as well as his impressive luxury yacht in a cinema newsreel film at: **https://youtu.be/RewUzmuD-_c**

Second attempt

Another opportunity arose in 1924, when Mars next came into close proximity with the Earth. This time, serious effort was made to detect any transmissions from the planet. Over in the US a 'National Radio Silence Day was declared over a 36-hour period from 21–23 August 1924, when many transmitters were stilled in order to detect extra-terrestrial signals. A radio receiver was lifted 3km off the ground to detect Martian transmissions, with a cryptographer at hand to translate any messages. Nothing was heard.

In London, however, wireless experts were more successful, hearing strange noises that could not be identified as coming from any earthly station. Early on 23 August the Associated Press reported that the attempt was made on a 24-valve receiver erected on a hill at Dulwich, with representatives of the Marconi Company and London universities present. The sounds were likened to harsh dots, but they could not be interpreted as any known code. The noises continued on and off for three minutes, in groups of four and five dots.

That was the last time anyone (possibly) heard from the Red Planet, and subsequent research was directed towards radio astronomy rather than communication with other planets, as you can read at: **http://bit.ly/pe-aug19-tt3**

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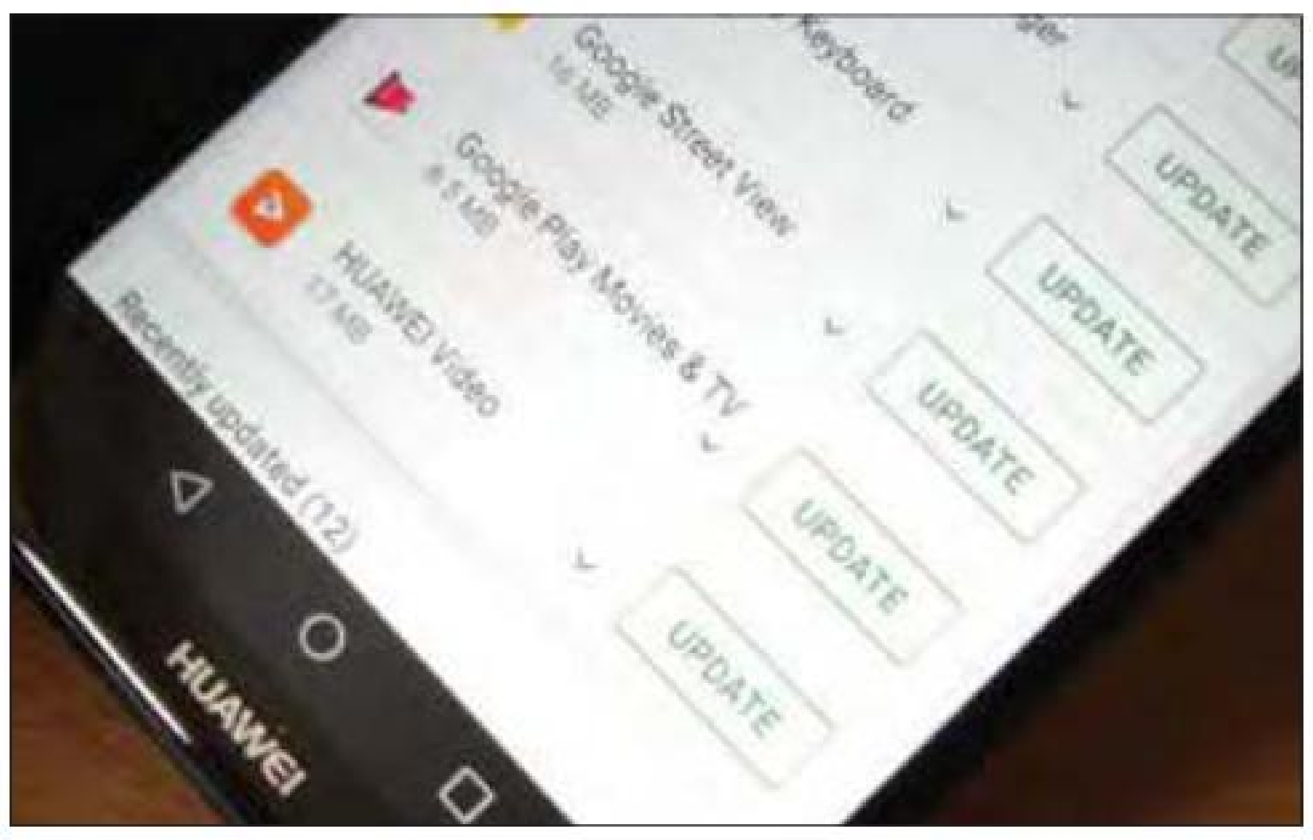
Net Work

Alan Winstanley

This month, the conflicting requirements of security, cooperation and trade that lie at the heart of the Huawei debate; plus, the latest broadband-from-space news.

Earlier this year, fearing that America's digital infrastructure could be vulnerable to cyber attack by foreign powers, the US President declared the potential risk to state security by foreign-made IT equipment and services to be a national emergency. In May, he signed an executive order on, *Securing the Information and Communications Technology and Services Supply Chain*. It cites the 'potentially catastrophic results' that hidden vulnerabilities in such equipment might have on the US economy and its security, and it banned the purchase of both individual and entire classes of IT infrastructure hardware and services designed or manufactured by any source that was owned or controlled by a 'foreign adversary'. No names were mentioned though.

Soon afterwards, the US Government accused Chinese telecoms manufacturer Huawei of illegally re-exporting goods or services from the US to Iran. That was enough for the US Bureau of Industry and Security to slap a ban on Huawei and 68 affiliates by adding them to its 'Entity List', effectively barring US industry and commerce from dealing with them. The order did not specifically mention IT hardware or vulnerabilities in Huawei equipment, but it still torpedoed the idea of American firms trading with the Chinese telecoms giant. If they tried 'exporting' to Huawei, a license would be denied by default, which matters a lot when exports of key US software, semiconductors and technology are involved. The suggestion is that such Chinese-made enterprise hardware could become a cybersecurity risk by providing a back door for eavesdropping by the Chinese state. Huawei has been at pains to declare its independence, but the perceived risk of China ordering Huawei to co-operate with state-sponsored espionage or cyber attacks in the future is undiminished, at least in the minds of the US authorities.



Current Huawei Android devices are still receiving Google updates – for now.

5G gets the green (traffic) light

Networks are racing to roll out high-speed 5G networks and the first commercial 5G service is already operational in Switzerland, powered by Ericsson. The Russian mobile operator MTS is adopting Huawei 5G technology, and in Japan, 5G base stations are being fitted into 200,000 traffic lights. They could ultimately interface with self-driving vehicles and also be used for emergency crisis communications. The British Telecom mobile brand EE has also launched the first 5G service in Britain, incorporating Huawei gear on the 'edge' of the network (see this month's *Fox Report*).

Britain's initial response to the Huawei 'emergency' has been to restrict Huawei equipment from the core of the country's communications network, but not from the network 'edge'. Increasing doubts and suspicions about Huawei's enterprise hardware resulted in the creation of the Huawei Cyber Security Evaluation Centre (HCSEC) in 2010 in partnership with the UK Government's National Cyber Security Centre (NCSC). This recently enlarged, Huawei-funded lab was designed to lift the 'bamboo curtain' surrounding the Chinese firm's hardware, proprietary source code and its UK strategies.

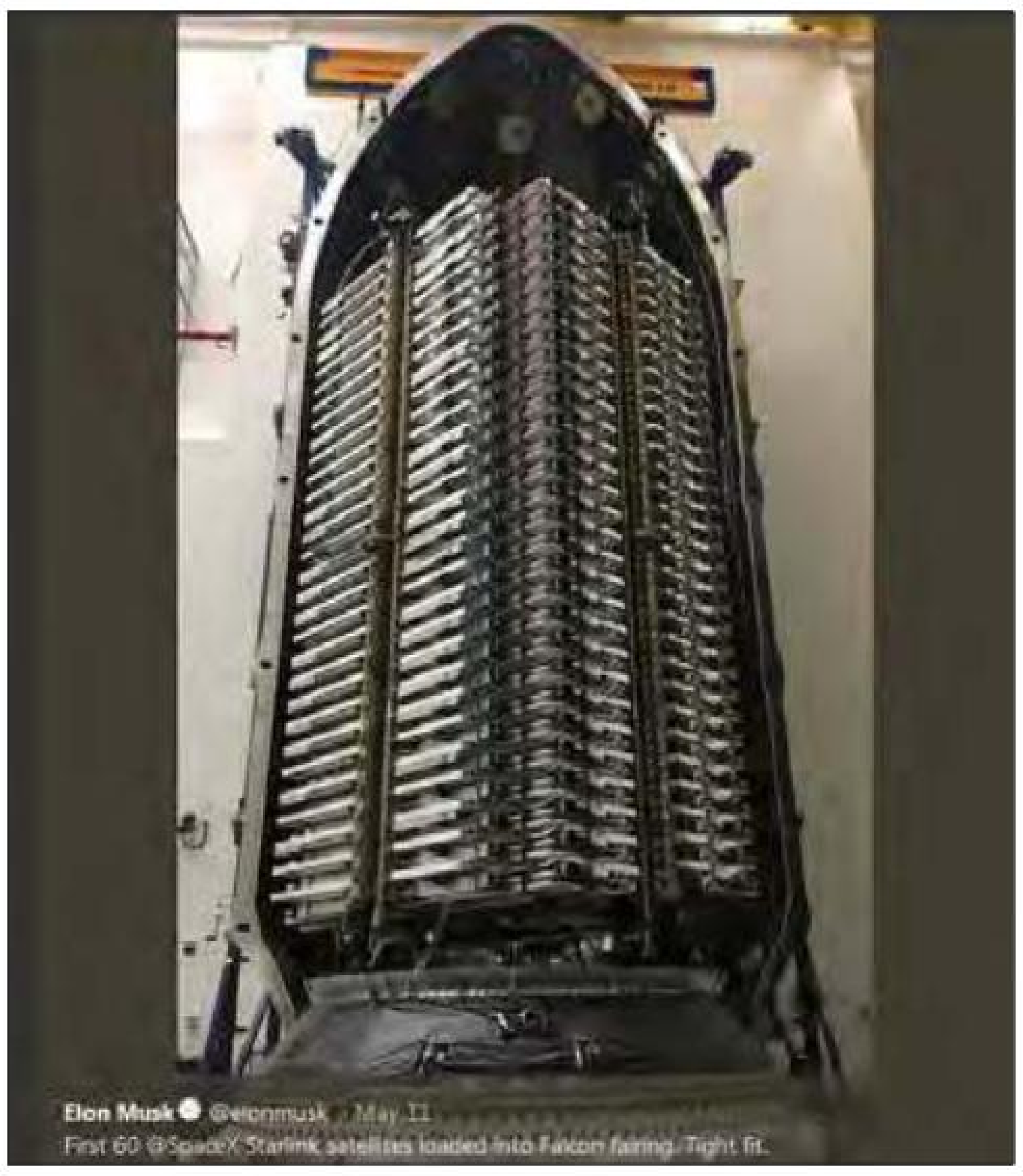
The centre uses security-vetted Huawei staff overseen by the NCSC, which employs world-class cyber security experts of its own, and security is as rigorous as it possibly can be. Huawei also opened a Cyber Security Transparency Centre in Brussels in March this year. (In the same way, Russian antivirus vendor Kaspersky, whose software suffered a US Government ban in 2017, opened a data and transparency centre in Zurich, and a further one is planned in Madrid this year to address any suspicions about covert state intervention.)

The *2019 HCSEC Annual Report* by its Oversight Board gives readers no sense of confidence in the Huawei network equipment and systems that have been examined so far. A number of software and cyber security management shortcomings were highlighted, with 'several hundred' system vulnerabilities being noted along with failures to remedy some earlier ones that were expected to be fixed by now. Some serious vulnerabilities were found that created significant and fundamental risks. The report cited poor software engineering practices and quality issues and was also critical of Huawei's codebase security management.

Mitigating risks

In one example, the Oversight Board found that an unworkable number of different versions of OpenSSL components were being used, some having known vulnerabilities and were unsupported anyway. Improvements had been made but the report criticised 'poor configuration management, product architecture and component lifecycle management'. Sloppy coding practices were evident and the report stated how, 'Huawei's own internal secure coding guidelines are not routinely followed [in this product] and, in some cases, developers may be actively working to hide bad coding practice rather than fix it.'

Britain's cybersecurity agency reckons that the best approach to mitigate such defects is to risk-manage them under NCSC scrutiny and design them out of existing and future infrastructure. They consider that identifying such problems in the first place is positive evidence of a quality system working properly, but significant issues in Huawei's software engineering and cybersecurity regime still remain. They needed convincing that Huawei was truly committed to change and improvement in all products across the


Elon Musk @elonmusk · May 11
First 60 @SpaceX Starlink satellites loaded into Falcon fairing. Tight fit.

A stack of 60 Starlink satellites fitted tightly into a SpaceX Falcon fairing.

board, given that robust assurances dating back many years had yet to materialise: Huawei had accepted the criticisms made and promised to spend $2 billion in the next five years in company-wide quality improvements. In the meantime, a whole raft of flaws and vulnerabilities remain – and having picked on Huawei, we cannot know the state of equipment produced by its rivals.

Last year, Australia soft-launched its own 'Telecommunications Sector Security Reforms' (TSSR) and has already gone further than Britain by banning both Huawei and ZTE from the country's 5G roll-out altogether: a difficult move for a country whose economy depends to some degree on exports to China. So far, '[The Australian] Government has found no combination of technical security controls that sufficiently mitigate the risks,' their press release stated at the time.

Current affairs

What does the US ban mean for current owners? At the time of writing, Huawei is still advertising its latest high-end mobile phone – the P30 Pro – on British TV. The knock-on effects of the US ban are still unfolding, but a 90-day extension to 19 August was granted to allow Google to continue updating Huawei and Honor-brand Android devices that were already in use or on sale. Nothing was said about offering services beyond that date, but on Twitter @Android was clear and tweeted that 'services like Google Play & security from Google Play Protect will keep functioning on existing Huawei devices'. If so, the best case outcome is that Android devices that are already licenced by Google will still be supported as normal. Worst case, users would be blocked from updating their apps via Google Play Store. Malware protection via Play Store Protect would cease and, worse, cloud-based services like Google Maps and Google Assistant would stop working, as would Google Home and Google Nest, ultimately disabling control of any user's IoT devices that rely on them.

Huawei will also be barred from accessing future versions of Google's Android ('Q'). If a mobile banking app demands the latest version of Android in the future then current Huawei owners will be left high and dry. There is much talk of Huawei developing its own OS devoid of Google, based on the open source version of Android, and building a compatible rival to Play Store, but we have already seen what British cyber experts think of Huawei's coding skills so far. No-one really knows what will happen next.

More space traffic

The broadband-from-Space season continues with the news that a towering stack of 60 SpaceX 'Starlink' satellites was launched from Florida at the end of May on board a SpaceX Falcon 9 rocket. The cluster of satellites sparked a UFO alert in Holland when they passed over the Netherlands. The constellation of satellites was successfully released into a low-earth orbit (LEO) where they were allowed to gradually drift into position, with krypton-based ion thrusters fine-tuning their location. The rocket's first stage landed vertically on a floating landing pad in the Atlantic – a remarkable achievement – where it could be recovered for re-use in future missions.

Designed with low cost, mass production in mind, the array of quarter-tonne satellites signals the foundation of a new low-latency satellite system that SpaceX hopes will relay 'broadband' data back down to earth via a number of ground stations. Up to 12,000 such Starlink satellites may circle in low-earth orbit one day, but astonomers are less enthusiastic about the increasing numbers of such satellites that are parking themselves in this relatively quiet zone above the Earth. The International Astronomical Union (IAU) cautions about the potential risk of such satellites interfering with their research. After all, an aircraft flying overhead at 35,000 feet (nearly seven miles, or over 10km) can be seen with the human eye when it reflects sunlight, and so sun glinting off a passing satellite could be misinterpreted by the astronomer's ultra-sensitive instruments; RF communications data could also be affected by them as well, the IAU fears.

A Starlink constellation readied for release into LEO.

For anyone interested in launching a payload into space themselves, the SpaceX price list starts at just $62 million for a Falcon 9, while the 27-engine 'Falcon Heavy' lifter is yours for $92 million a throw. For the curious – or serious entrepreneur – there is even a *Falcon User Guide*, downloadable from **http://bit.ly/pe-aug19-spx** that offers an insight into some of the complexities behind this exciting new wave of private-enterprise space technology.

Newsbeat

A quick roundup of other news: Amazon hopes to help small online traders take their first steps into physical retailing on the High Street. Its year-long pilot 'Clicks and Mortar' plan will see ten pop-up stores appear across the UK, building up to a total of 100 small boutique-type businesses where buyers can touch and feel the merchandise.

Attention owners of older Windows PCs from XP up to Windows 7 – a remote code vulnerability in Remote Desktop Services has been discovered which could allow an unauthenticated attacker to run code on a target system. The loophole (CVE-2019-0708) is considered so serious that Microsoft even released an update for Windows XP, its legacy OS that has long been out of support, while Windows 7 should patch itself during routine Windows updates. A standalone update (search KB4500331) can be downloaded from Microsoft Update Catalog at: **http://bit.ly/pe-aug19-nw1** which installed on an XP machine without a hitch. Visit the Microsoft Security Response Center at: **http://bit.ly/pe-aug19-nw2** for details. Interestingly, Microsoft acknowledged the UK's National Cyber Security Centre for its expertise in plugging this vulnerability.

Alibaba's efforts to confound the author with more zany suggestions for 'hot buys' continue: this month's offers include a dockside crane, a tunnel borer similar to the Thunderbird 2 'Mole' and a mountain bike! See you next month.

The author can be reached at:
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Brainwave Monitor

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by Jim Rowe

Brains produce tiny signals which can be detected by an EEG monitor. This project can not only do that – monitor and display brainwaves on a computer screen – but also save and print them. It is based on an Arduino Nano and connects to a PC via a USB cable.

There are many reasons why brainwave monitoring can be useful. It can help in assessing your own well-being but few people have the ability or means to do it. They can only get information on their own brainwaves if they are referred to a specialist clinic – and the most common of these would be for investigation of sleep apnoea.

But you don't have to be suffering from this serious complaint to have a reason to have your brainwaves monitored and investigated – with this inexpensive project, you can do it yourself.

Brainwaves are monitored using a number of electrodes placed on the scalp. These are readily available and not expensive. The electrodes are connected via shielded leads to the *Brainwave Monitor* unit, which then connects to a portable computer to display the results.

The design for this *Brainwave Monitor* is partly based on the circuitry of the *Electrocardiogram* (ECG) project in the October 2016 issue. That project only needed a single channel and two electrodes to monitor electrical activity in a human heart.

This *Brainwave Monitor* has three channels to monitor multiple electrodes. The minute (tiny, not time!) signals are fed to very-high-gain amplifiers which are filtered and fed to a low-cost Arduino Nano microcomputer module to convert the signal readings to digital values, which are then sent to a PC for display and analysis.

In a little more detail, since the voltages picked up by the brain electrodes are so small, the main board has three high-gain differential input amplifiers, each of which includes a three-pole low-pass filter to reduce the devices' susceptibility to 50Hz hum radiated by mains power cables and other equipment.

The *Brainwave Monitor* is powered from the PC via the USB cable, so there's no need for a separate power supply. The total current drawn is less than 45mA (at 5V).

The *Brainwave Monitor's* functions are controlled using a Windows-based GUI application written in Visual C++.

How it works

The Arduino Nano microcomputer module provides both a multi-channel analogue-to-digital converter (ADC) and a USB interface. The software loaded onto this module uses these features to continually sample the analogue voltages from the front-end and sends the digitalised values to your PC via the USB interface.

Fig.1 shows the block diagram, which depicts the three high-gain differential amplifiers with low-pass filters that process the EEG signals to prepare them for sampling.

Capturing EEG waveforms is challenging because the voltages found on the surface of the scalp are tiny: between 10µV and 100µV peak-to-peak, depending on the positions of the electrodes on the scalp and the contact resistance. Hence the need for amplifiers with very high gain.

To make the job harder, these voltages are completely swamped by 50Hz hum (60Hz in the US and some other parts of the world), picked up by our bodies from the fields surrounding the AC wiring in our homes and offices

Luckily, while we are interested in the voltage differences between each pair of electrodes, the 50Hz hum picked up is virtually the same throughout the body. In other words, the 50Hz hum is a common-mode signal, while the EEG voltages are differential-mode signals.

So by using an accurately balanced differential amplifier as the input stage of each EEG amplifier channel, we can cancel out most of the common-mode 50Hz hum but amplify the differential EEG voltages.

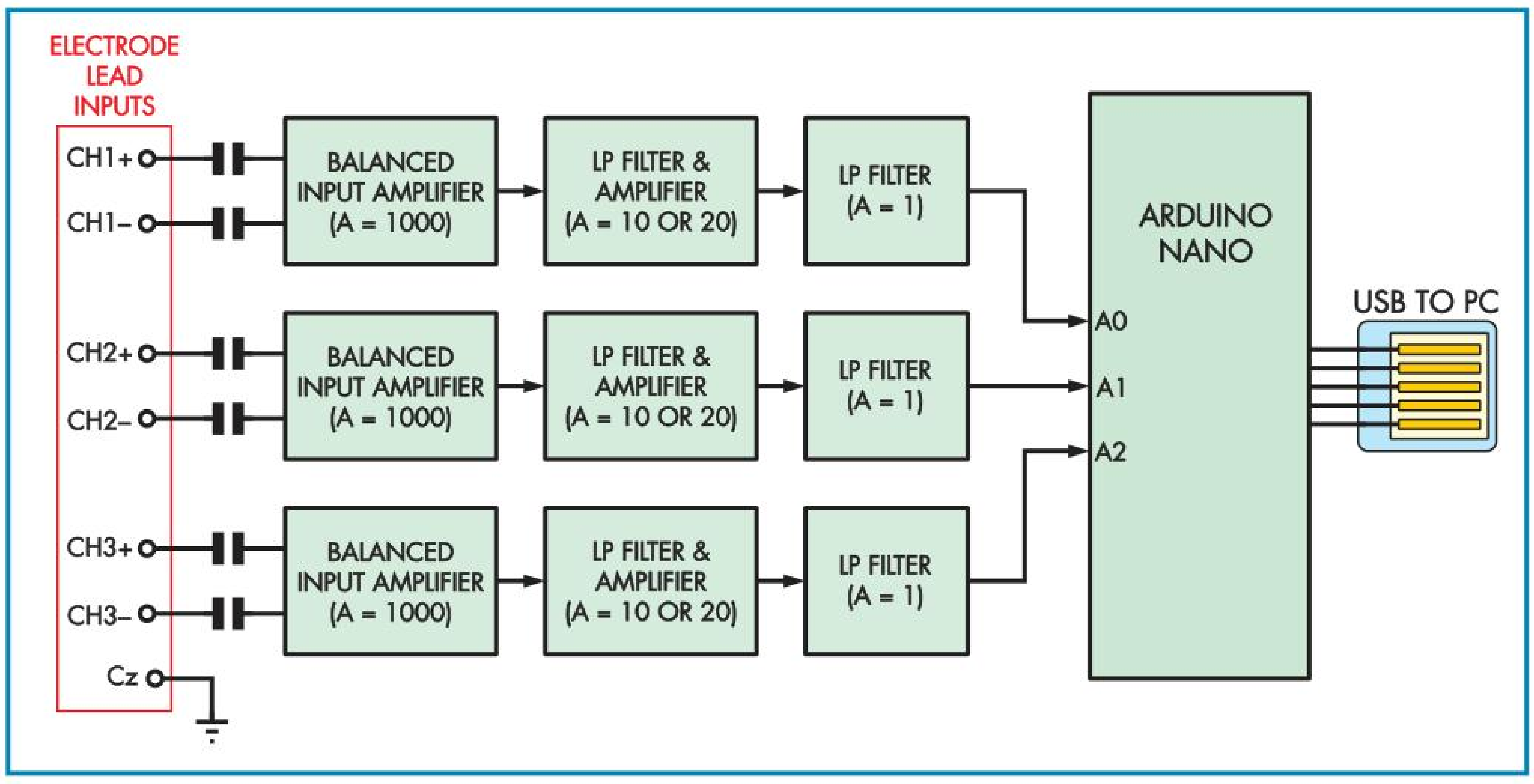
This project has not been designed for medical diagnosis

Correct interpretation of EEG waveforms is a complex and skilled procedure and requires proper medical training. The *Brainwave Monitor* is presented here as an instructive and educational device only. If you have any concerns about the health of your brain, consult a healthcare professional with specialist knowledge in this area.

The connections between the electrodes and the subject's scalp need to be good because if one connection is poor, this can upset the balance of that input amplifier and reduce the common-mode cancellation.

Another method to reduce the hum pickup is to connect a ground electrode to the top centre of the subject's scalp, called the 'Cz' position.

Most of the remaining 50Hz signals are removed by low-pass filtering in the later stages of each amplifier. As a result, the output of the amplifiers provide clean amplified EEG signals, with insignificant residual 50Hz (or 60Hz) hum.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Cz
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BALANCED INPUT AMPLIFIER (A = 1000)
LP FILTER & AMPLIFIER (A = 10 OR 20)
LP FILTER & AMPLIFIER (A = 10 OR 20)
LP FILTER & AMPLIFIER (A = 10 OR 20)
LP FILTER (A = 1)
LP FILTER (A = 1)
LP FILTER (A = 1)
ARDUINO NANO
A0
A1
A2
USB TO PC

Fig.1: A simplified block diagram of our *Brainwave Monitor*, showing the three input amplifiers processing the tiny EEG signals and boosting them to feed the ADC inputs of the Arduino Nano.

Circuit description

The full circuit of the *Brainwave Monitor* is shown in Fig.2. The shielded electrode leads are wired up to CON1, a DB9F connector. The six differential signals for the three channels are then fed through 1µF capacitors and series 4.7kΩ resistors to the inputs of IC1, IC3 and IC5. These are Analog Devices AD623ARZ chips, which are instrumentation amplifiers with very high common-mode signal rejection and high gain.

The overall differential-mode gain of each AD623ARZ device is set by a resistor connected between pins 1 and 8. A value of 100Ω gives a gain of 1000 (60dB).

To ensure that IC1, IC3 and IC5 deliver maximum undistorted output level and the analogue signals fed to the Arduino span its entire 0-5V ADC range, we feed 2.5V DC (half the 5V supply voltage) to each amplifier's reference signal input (pin 5) from a low-impedance source. This sets the DC level of the amplifier output signals to 2.5V. This half-supply reference is provided by voltage reference REF1 (an LMV431BIMF), which sets the zero-signal output level of IC1, IC3 and IC5. The two 2.2MΩ input bias resistors for each input amplifier are returned to the same +2.5V point, providing identical biasing for the amplifier inputs.

Since the input amplifiers are being operated with such a high gain, we also need to prevent them from amplifying any stray RF signals which may be picked up by the electrode leads (or the subject's head and scalp). These signals are filtered out by the 1nF bypass capacitors between each amplifier input and ground, and also the 47nF capacitors between each pair of inputs.

These capacitors form a balanced low-pass filter, in conjunction with the two 4.7kΩ input series resistors, with a –3dB point of 350Hz. Thus, the filters will be very effective at attenuating RF signals at hundreds of kilohertz and above, while having no effect on the low-frequency EEG signals.

The rest of the *Brainwave Monitor's* amplifier and filter circuitry is based around IC2, IC4 and IC6, all of which are LMC6482 CMOS-input dual low-power op amps. These have rail-to-rail capable inputs and outputs.

The following text describes the operation of the first channel; the other two are identical.

The output from IC1 is fed to the input of IC2a via a simple RC low-pass filter formed by a series 3.9kΩ resistor and the 1µF capacitor, which gives a corner frequency of about 40Hz and an attenuation of about –4dB at 50Hz.

IC2a provides an additional fixed amplification of either 20 or 10, depending on whether LK1 is present or not.

When LK1 is inserted, it shorts out the 220Ω resistor in the feedback path, altering the feedback ratio and thus increasing the stage gain to 20.

Either way, a parallel combination of two 220µF ceramic capacitors between the bottom of the feedback divider and ground ensures a good low-frequency response while eliminating any DC offset at the op amp output, which could otherwise lead to premature or asymmetric signal clipping.

IC2b provides additional low-pass filtering, to further reduce the 50Hz hum level. It forms a second-order Sallen-Key low-pass filter with a corner frequency of about 30Hz, giving

The Arduino Nano

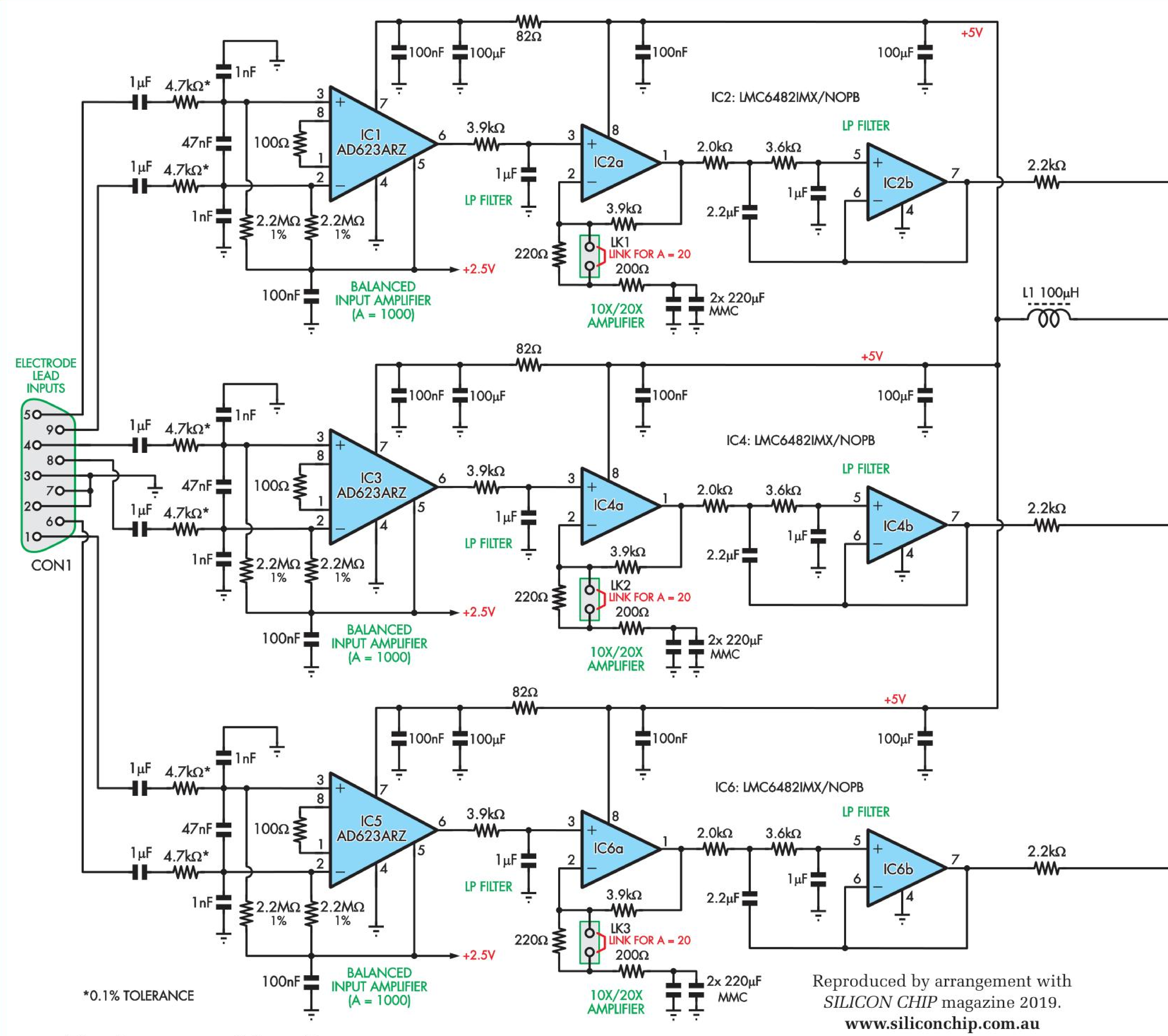
As explained in the circuit description, the Arduino Nano is the heart (or should that be brain?) of the Brainwave Monitor. It is effectively a miniaturised version of the familiar (and original) Arduino Uno. It's about a quarter the size, with a PCB measuring 43 x 17.5mm. Most connections to the board are made via two 15-pin SIL headers, fitted 15mm apart.

Like the Uno, this module is based on an Atmel ATmega328P microcontroller, but in this case, in a 32-pin SMD package. Instead of using a second ATmega16U2 microcontroller to handle USB communication with the PC, the Nano uses either an FT232RL or a CH340G USB transceiver chip. There isn't much else on the board, apart from an AMS1117 5V low-dropout regulator, 16MHz resonator and a tiny reset pushbutton.

Power comes from the PC via the USB mini type-B connector. Like the Uno and other Arduinos, the Nano also has a 6-pin DIL pin header for in-circuit serial programming (ICSP) of the microcontroller. Normally, you do not need to use this as you can program it using the USB port.

Inside the 328P chip is a reasonably fast 8-bit RISC processor with 32 registers, 32Kbytes of Flash memory, 1Kbyte of EEPROM and 2Kbytes of static RAM. There are also two 8-bit timer/counters, one 16-bit timer/counter, a real-time clock and calendar with its own oscillator, six PWM channels, a 10-bit ADC with eight input channels, a programmable serial USART, a master/slave SPI serial interface, an I^2C 2-wire serial interface and an on-chip analogue comparator.

When the Brainwave Monitor is working, the sequence of events is quite straightforward. Each time the software wants a set of EEG samples taken, it sends a command to the Arduino, which then uses its internal ADC to take 10-bit samples of the amplified EEG signals at its A0, A1 and A2 inputs. The sample values are then sent back to the PC, in a sampling cycle that takes less than 15 milliseconds.


ELECTRODE LEAD INPUTS
CON1
1µF
4.7kΩ*
1nF
47nF
100Ω
2.2MΩ 1%
100nF
IC1 AD623ARZ
IC3 AD623ARZ
IC5 AD623ARZ
BALANCED INPUT AMPLIFIER (A = 1000)
+2.5V
82Ω
100µF
+5V
3.9kΩ
LP FILTER
IC2a
IC2b
IC4a
IC4b
IC6a
IC6b
IC2: LMC6482IMX/NOPB
IC4: LMC6482IMX/NOPB
IC6: LMC6482IMX/NOPB
220Ω
LK1
LK2
LK3
LINK FOR A = 20
200Ω
2x 220µF MMC
10X/20X AMPLIFIER
2.0kΩ
3.6kΩ
2.2µF
2.2kΩ
L1 100µH
*0.1% TOLERANCE

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Brainwave Monitor
Arduino Nano based

Fig.2: the circuit is essentially two halves: on this page are the three identical high gain differential amplifiers which take their tiny inputs from the electrodes . . .

an attenuation figure of about 15dB at 50Hz, but with unity gain for the low-frequency EEG signals.

So at the output of IC2b (pin 7), we end up with relatively clean and hum-free EEG signals, amplified by either 10,000 or 20,000 times, depending on the setting of LK1.

This signal, along with the identically processed signals from the other two channels, are then fed to the A0, A1 and A2 analogue input pins of the Arduino Nano.

LED1, the power indicator, lights when the 5V supply is present, while LED2 lights when output pin D3 of the Arduino Nano goes high, which indicates that sampling is taking place.

Each of the ICs has a 100nF bypass capacitor which ensures it has a stable supply, while the supply to each instrumentation amplifier is independently filtered using an RC low-pass filter made up of an 82Ω series resistor and 100µF ceramic capacitor to ground, to minimise cross-talk between amplifiers.

These also prevent noise being coupled into the sensitive front-end amplifiers from the 5V USB supply.

The 5V USB supply for the whole circuit is also filtered by an LC low-pass filter comprising a large, high-frequency 100µH series choke (L1) and three paralleled 100µF ceramic capacitors to ground.

This LC filter is in series with the individual RC filters to each instrumentation amplifier, so they combine to provide excellent noise rejection.

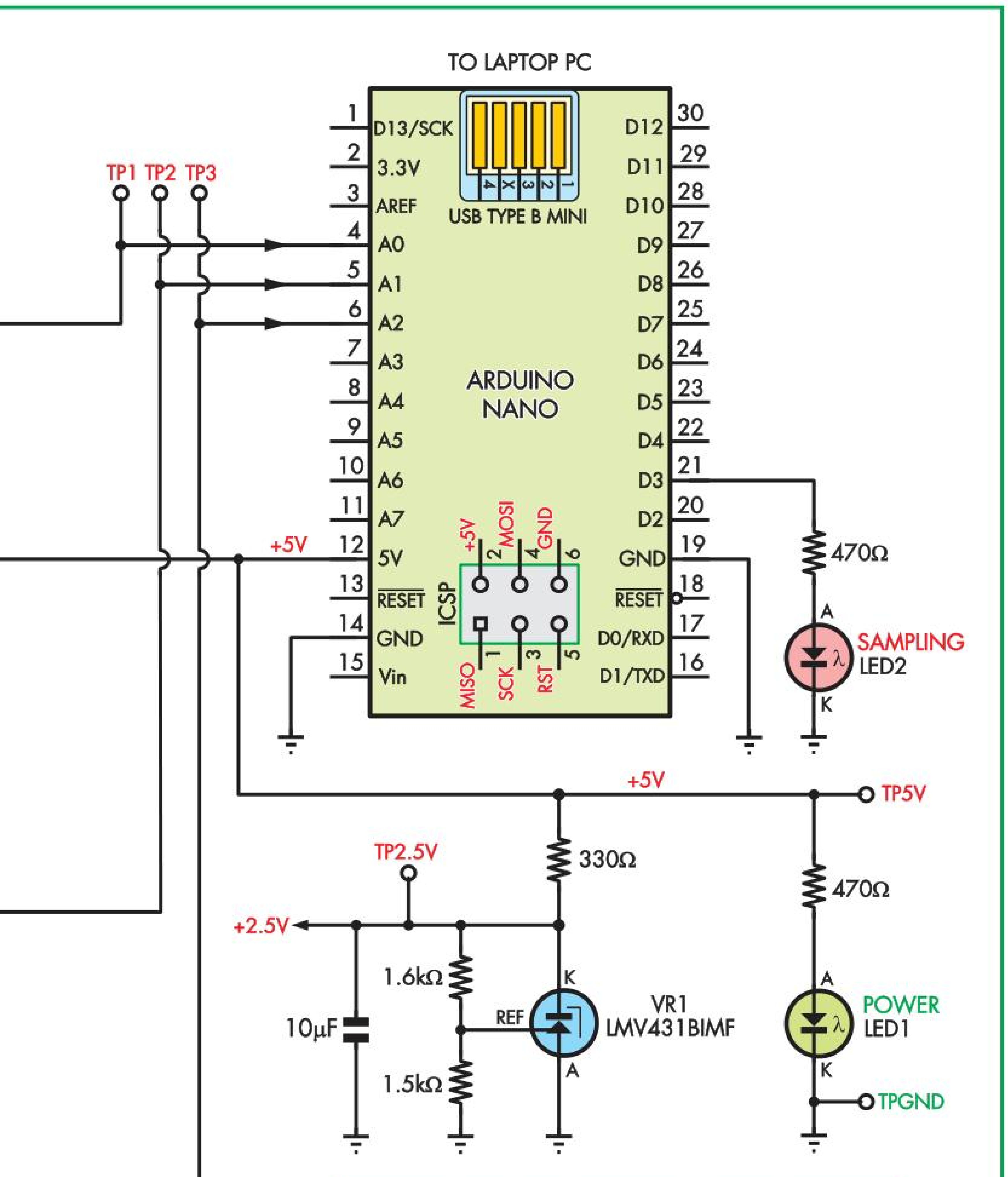
Construction

All of the *Brainwave Monitor* circuitry, including the Arduino Nano, is mounted on a PCB measuring 109.5 × 83.5mm, coded 25108181 and available from the *PE PCB service*.

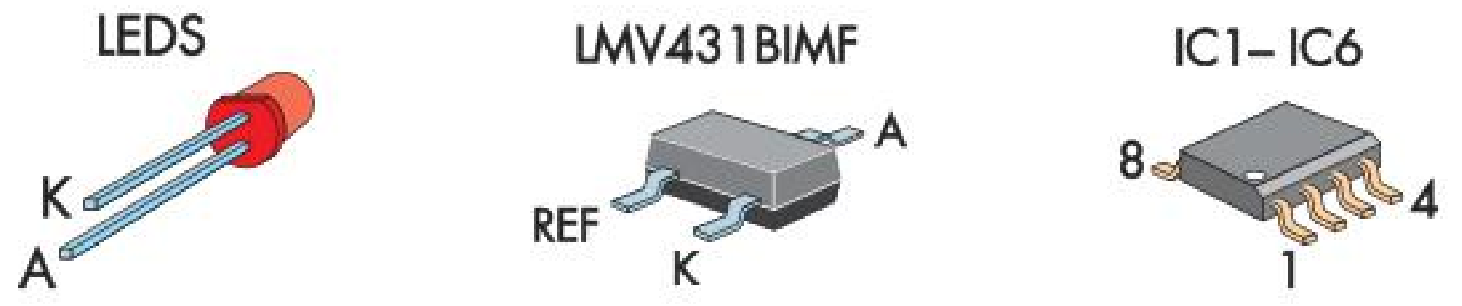
Use the PCB overlay diagram shown in Fig.3 as a guide for fitting the components to the board. Many of the components on the PCB are SMDs (surface-mount devices) but there are some through-hole parts too.

Fortunately, the SMDs are quite straightforward to solder as they have fairly large and widely spaced pins.

Fit the SMD resistors first, followed by the SMD capacitors and then the six ICs. The main thing to watch with the ICs is to orient them correctly, as shown on the overlay diagram.



CON1 PIN – INPUT CONNECTIONS	
CON1 PIN	CONNECTION
1	Channel 3 + input
2	(Ground Reference)
3	Ground Reference (Cz – top centre of skull)
4	Channel 2 + input
5	Channel 1 + input
6	Channel 3 – input
7	(Ground Reference)
8	Channel 2 – input
9	Channel 1 – input



. . . while on this page is the Arduino Nano which processes the signals from the amplifiers.

Parts list – Brainwave Monitor

1 PCB, code 25108181, 109.5 x 83.5mm
1 Diecast aluminium box, 119 x 93.5 x 34mm
1 Arduino Nano or equivalent module
1 USB cable, type A to mini-B
1 DB9F/DE9 socket, right-angle PCB-mounting (CON1)
  [Jaycar PS0806, Altronics P3030]
1 100µH 1.6A SMD inductor (L1)
  [Murata 48101SC; element14 Cat 2112367]
3 2-way SIL pin headers with jumper shunts (LK1-LK3)
7 PCB terminal pins (optional)
4 M3 x 10mm metal tapped spacers
8 M3 x 6mm panhead machine screws
4 small adhesive rubber/plastic mounting feet

Electrode components

7 EEG electrodes
7 26mm insulated alligator clips (three red, four black)
  [4 x Jaycar HM3020]
1 DB9M plug with backshell cover
  [Jaycar PP0800+PM0812, Altronics P3000+P3093]
1 3.6m length of figure-8 shielded stereo audio cable
1 1.2mm length of green light-duty stranded, insulated wire
1 150mm length of 4mm diameter heatshrink tubing

Semiconductors

3 AD623ARZ instrumentation amplifiers, SOIC-8 (IC1, IC3, IC5)
3 LMC6482IMX dual op amps, SOIC-8 (IC2, IC4, IC6)
1 LMV431BIMF adj. precision shunt regulator, SOT-23 (REF1)
1 3mm green LED (LED1)
1 3mm red LED (LED2)

Capacitors (all SMD ceramic except where noted)

6 220µF 6.3V X5R dielectric, 1210 size
6 100µF 6.3V X5R dielectric, 1206 size
1 10µF 25V X5R dielectric, 1210 size
3 2.2µF 25V X5R dielectric, 1206 size
6 1µF 100V MKT (leaded)
6 1µF 16V X7R dielectric, 1206 size
9 100nF 16V X7R dielectric, 1206 size
3 47nF 50V X7R dielectric, 1206 size
6 1nF 50V C0G dielectric, 1206 size

Resistors (all 0.125W 1% 1206 size SMD)

6 2.2MΩ 2 20kΩ 1 11kΩ 1 10kΩ 1 11kΩ
9 10kΩ 6 3.9kΩ 3 3.6kΩ 1 2.7kΩ 3 2.2kΩ
3 2.0kΩ 1 1.6kΩ 1 1.5kΩ 2 470Ω 1 330Ω
3 220Ω 3 200Ω 3 100Ω 3 82Ω
6 4.70kΩ 0.1%

For all these components, it's easiest to tack-solder one pin first, double-check the component orientation and/or value, then solder the other pin(s) and refresh the first solder joint.

If you accidentally bridge adjacent pins with solder, simply remove the excess using a small dob of flux paste and apply some braided solder wick.

Using the same technique, you can now mount REF1 (in a small SOT-23 package) and the largest SMD component, L1. Then all of the leaded/through-hole parts can be added, starting with the three 2-pin headers for LK1-LK3, then the six 1µF input coupling capacitors.

Next, fit CON1, making sure that all of its nine pins pass down through their mounting holes, along with the two mounting lugs. Make sure that the connector's body is resting on the top of the PCB before you solder all the pins under the PCB.

Now install the LEDs with their leads straight, with the underside of each lens 12mm above the top of the PCB. Make sure they are oriented correctly, ie, with the longer (anode) lead soldered to the pad marked 'A' on the PCB. Then bend the leads forward by 90°, 7mm above the top of the PCB.

Then, if you want them, add the seven optional PCB terminal pins, (used for test points).

If you've purchased a clone instead of a genuine Nano, it may be supplied with separate headers.

In this case, you will first need to solder the headers to the Nano board,

SAFETY WARNING

To ensure complete safety, this *Brainwave Monitor* must *only* be used with a battery-powered laptop or notebook PC, ie, one that is NOT connected to the mains in any way. Do NOT use it with a desktop or laptop PC that is powered from 230VAC.

This precaution is necessary to eliminate the remote possibility that a fault in the power supply of a mains-powered PC could result in a high AC voltage being applied to the EEG electrodes attached to the scalp, which could have fatal consequences.

ensuring that the solder joints are made on the top side of the module, with the plastic strips and long pins underneath (see photos).

Now mount the Arduino Nano on the PCB, with its USB mini-B connector facing towards the top and its two 15-pin headers passing down through the matching holes in the PCB. Make sure the plastic strips which hold each row of pins together are resting on the top of the main PCB before you solder the pins underneath.

That concludes the assembly work on the *Brainwave Monitor* PCB.

Installing the software

Before mounting the PCB in its case, first verify that it's working properly. You'll need to establish communications between the Arduino Nano module and your PC, then you will need to load the Arduino firmware and PC software. You can then verify it's all working before going any further.

Fig.6 gives an overview of how the *Brainwave Monitor* works with the software installed on your computer.

If you don't already have the Arduino IDE (integrated development environment) installed on your computer, download and install it now.

The download is free and it's available for Windows, macOS and Linux systems (but note that the main software program written for this project is for Windows only).

You can download the Arduino IDE from: **https://www.arduino.cc/en/Main/Software** The latest version at the time of writing is 1.8.5 so we suggest you use this or a later version if possible, to ensure compatibility.

Having installed the IDE, plug the Nano board into one of your computer's USB ports (LED1 on the PCB should light up) and then start the IDE. Open the Tools → Ports menu and check the list to see if the Arduino Nano is present. If so, select it.

If it is not, that suggests that your computer may not have the appropriate USB/serial driver. Most systems will have this driver pre-installed, but in some cases, it may not.

In that case, refer to the two following links for instructions on installing the FT232RL or CH341 driver, depending on which chip your Nano has been supplied with: **http://bit.ly/pe-aug19-bw1** or **http://bit.ly/pe-aug19-bw2**

Once the driver is installed, re-plug the Nano, re-launch the IDE and check that the device is now showing up in the Ports list. Select it, and ensure that the Nano is also selected in the Tools → Boards menu.

You will now need the Arduino sketch, which you can download in a package from the *PE* website. The sketch file is called **sketch_for_EEG_Sampler.ino** and when the download is complete, unzip the files and open this sketch file using the Arduino IDE.

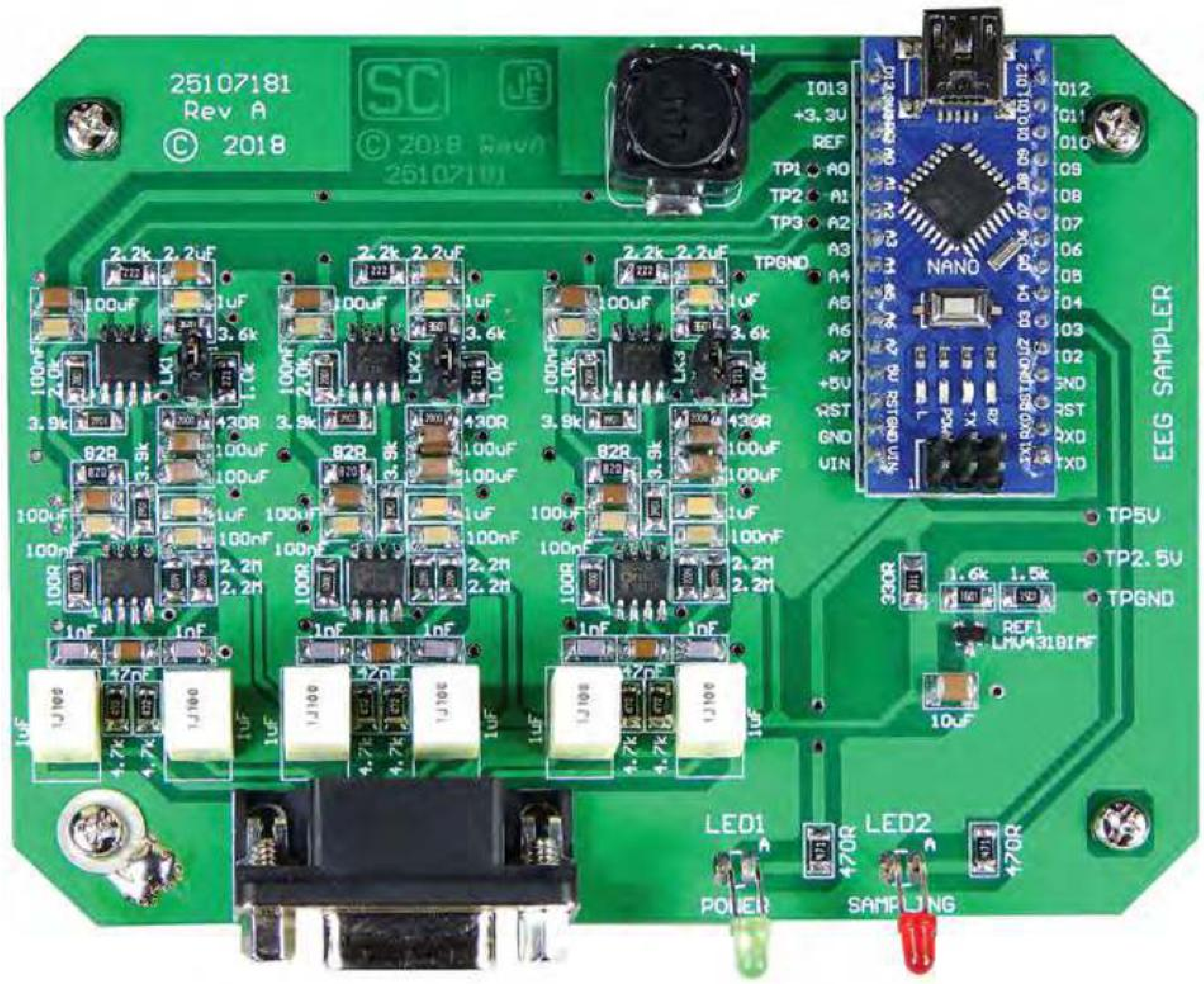
If you have set the Port and Board correctly (as above), you will just need to use the Tools → Upload menu option and the sketch should be compiled and uploaded onto the Arduino Nano. Your *Brainwave Monitor* is then ready to go. You just need the matching Windows software loaded on your PC.

Testing

Now close the Arduino IDE. You will need to install the Windows program on your computer to test out the *Brainwave Monitor*.

It's available from the *PE* website – **SiliconChipEEGSamplerSetup.exe**. Run this setup program and follow the prompts to install it. When that is complete, launch the software.

Select the correct COM port (the same one that was used to upload the sketch earlier) and set the baud rate to 115,200. Start sampling and check that the software is able to connect to the *Brainwave Monitor* and displays some traces. Of course, at this point the traces will probably just show noise. But at least you will have a pretty good indication that everything is working.



While there are quite a few SMD components to fit, they're all wide-spaced-pin types so they shouldn't cause you any grief when soldering.

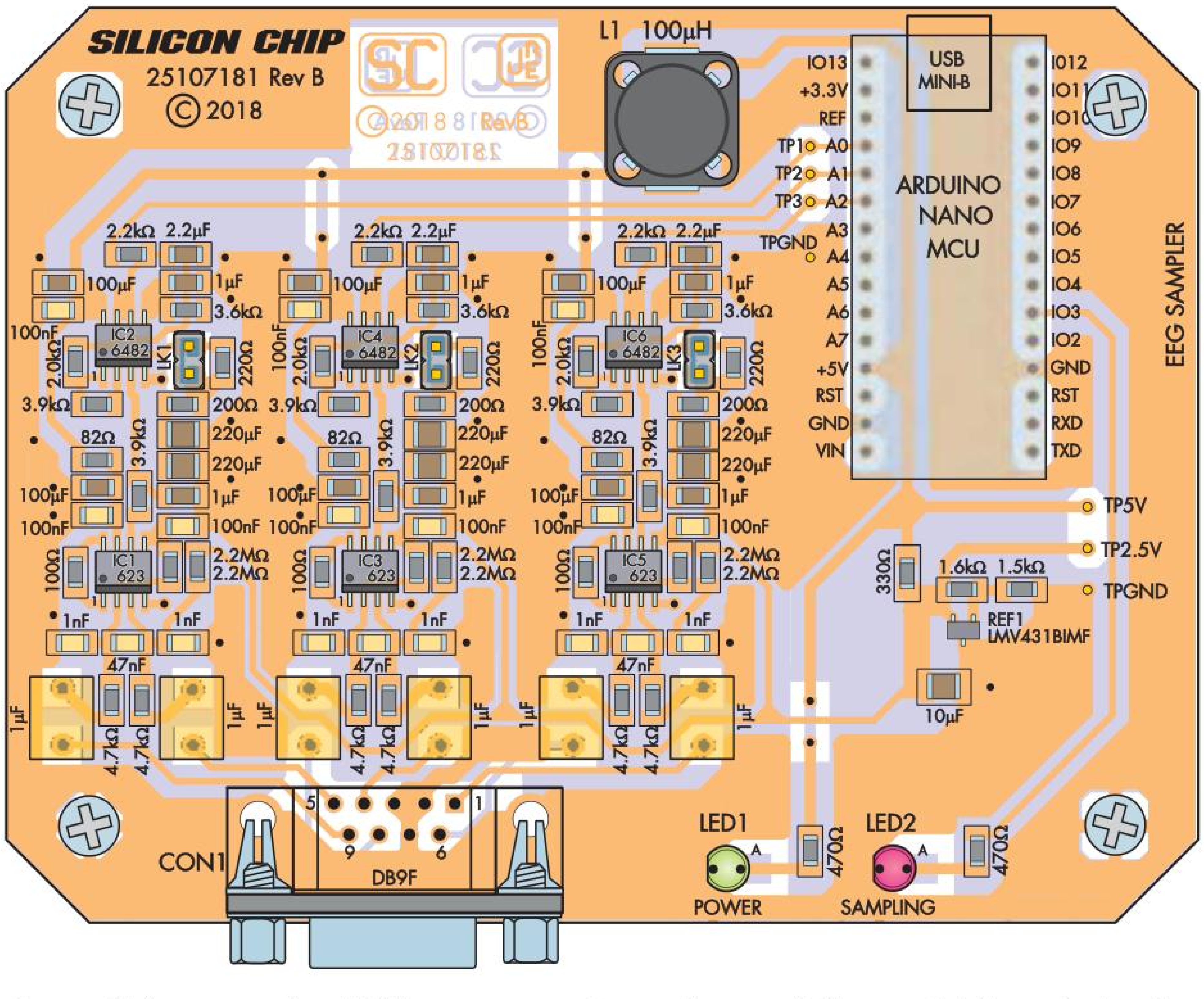
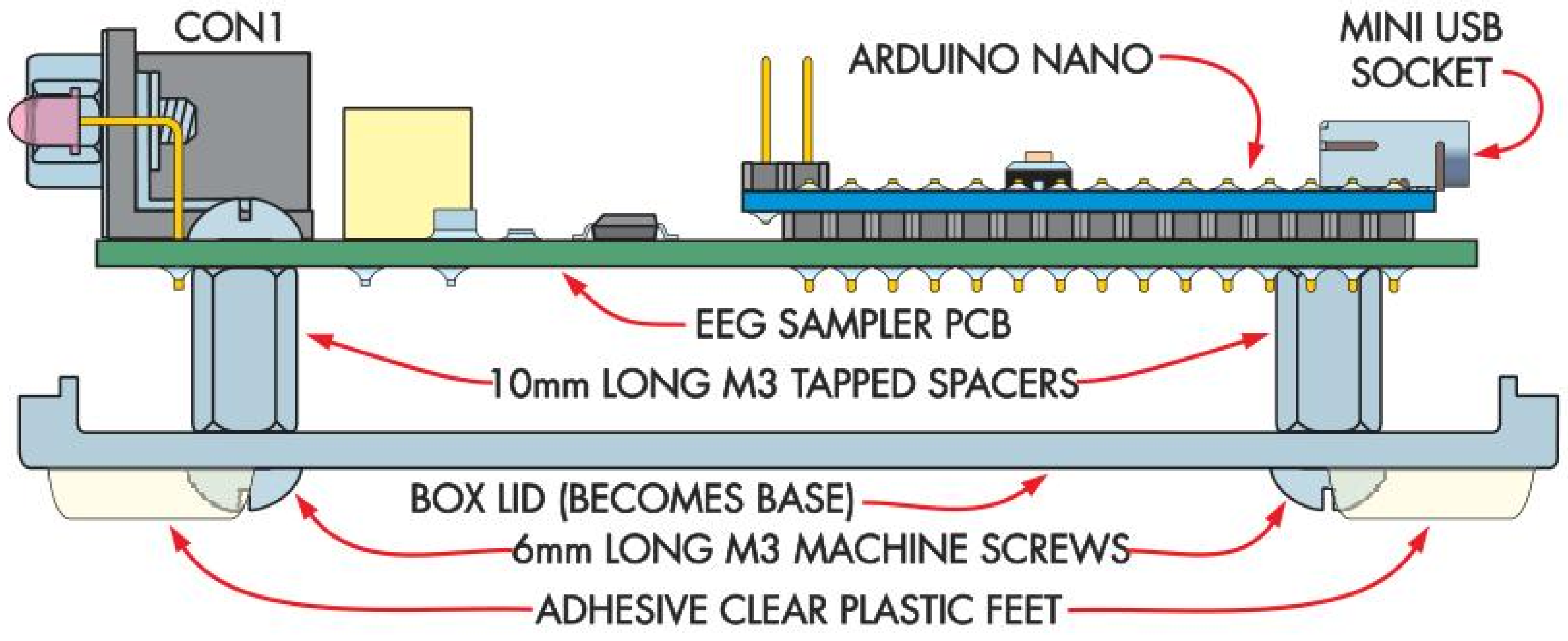


Fig.3: use this same-size PCB component overlay, and the matching photo above, when assembling the PCB.


CON1
ARDUINO NANO
MINI USB SOCKET
EEG SAMPLER PCB
10mm LONG M3 TAPPED SPACERS
BOX LID (BECOMES BASE)
6mm LONG M3 MACHINE SCREWS
ADHESIVE CLEAR PLASTIC FEET

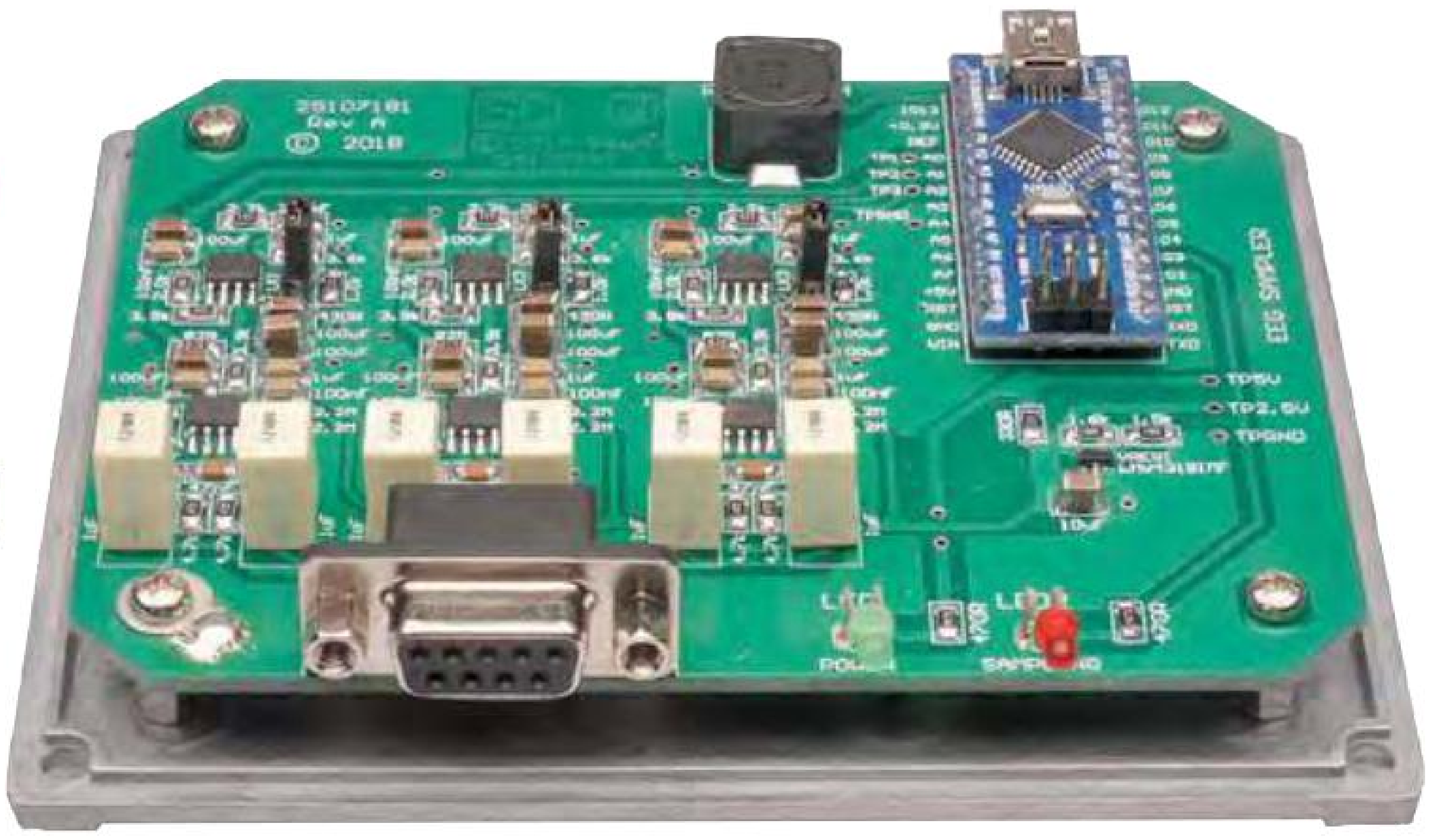


Fig.4: the completed PCB is mounted on the lid of the diecast case via screws, nuts and spacers, as shown here. The lid is then turned upside-down to become the base, as shown in the photo at right.

You can run your fingers along the 9-pin connector pins to check that each channel is being correctly sampled; this should induce some voltage on the inputs and cause a signal to appear, although it's likely to overload the channels, resulting in something that looks like a square wave.

Final assembly

The complete PCB assembly fits inside a standard diecast aluminium box measuring 119 × 93 × 34mm. The PCB assembly is mounted on the inside of the box lid with the box itself lowered down over the assembly to form a shielding enclosure; the lid then becomes the base.

Note that some of the diecast boxes we purchased recently had somehow missed out on the tapping of their mounting holes and we had to tap them by hand. So it would be a good idea to check the holes in your box before you begin final assembly.

The DB9F connector (CON1) used for the EEG electrode leads is accessed through a 31 × 17mm cross-shaped hole in the front of the box, with the two indicator LEDs protruding through a pair of 3.5mm holes to the right. The Arduino Nano's Mini-B USB socket is accessed via a 10 × 12mm rectangular hole in the rear of the box.

These holes in the case should be located and cut accurately so that the PCB assembly will fit properly. Refer to the drilling diagram, which can be downloaded as a PDF file from the *PE* website. Once the box has been prepared, you're ready for the final assembly stage.

The completed PCB is attached to the inside of the box lid using four 10mm-long M3 tapped metal spacers and eight 6mm-long M3 screws. Refer to Fig.4 for details.

Having mounted the PCB to the inside of the lid, fit the jumper shunts to LK1-LK3. This will set the gain of all three input channels to 20,000, which is the best setting to start with.

Now lower the main part of the case down over the PCB, tilting it at an angle of 20° or so at first so that CON1 and the two LEDs fit through the holes in the front of the case. You can then lower the back side down onto the lid, while at the same time moving the case slightly towards the rear. Once it's together, use the four supplied countersunk-head M4 screws to attach the lid to the case.

The final step is to apply a label to the top of the box. Like the box drilling diagram, the artwork for the dress front panel can downloaded as a PDF file from the *PE* website.

Either way, we suggest that you hot-laminate the artwork for protection against scratching and/or finger grease, and then attach it to the top of the box using double-sided adhesive tape or a thin smear of silicone sealant.

We suggest that you also fit four small adhesive rubber or plastic feet to the box lid/base, so the heads of the PCB mounting screws won't scratch any surface it's placed on.

The electrode leads

Although it's fairly easy to get hold of commercial EEG electrodes at relatively low cost, this isn't the case with electrode leads. They are available online but are generally expensive. Plus, most of them are not shielded and they are typically fitted with special line socket connectors for compatibility with commercial EEG machines.

So, regardless of which type of electrodes you use, the best approach is to make the leads yourself.

You can do this using a 3.6m length of *good quality* figure-8 shielded audio cable. Don't try to use cheap, ready-made stereo audio leads because they usually don't provide adequate shielding. They're made to a price, not a recipe!

Cut the cable into three 1.2m lengths. Remove 25mm of the plastic

Ch1
Ch2
Ch3
C2

(Let) Here's some commercial leads and attachments which we bought on the net – unlike the electrodes, which are pretty cheap, commercial leads are rather pricey. (Right) However, home-made leads, like the ones we made using crocodile clips and good-quality shielded figure-8 work just as well at a fraction of the price. Note the electrode labels – useful!

And here's how it looks on completion, with the front panel glued to the 'bottom' of the case – which is now the top! Ideally, the label should have a clear covering (eg, clear adhesive vinyl or even a laminate) to protect it from grubby fingers!

The crocodile clips of our 'DIY' leads grip the studs of low-cost self-adhesive electrodes. The electrode at lower right has been inverted to show its 'sticky ring' and the centre dob of conductive gel.

sheathing from one end of each cable and then unwind the exposed screening braid, twisting them together to form the earth connection wire.

Then remove about 6mm of the insulation around the inner conductors, after which you can tin the ends of both pairs of wires, ready for soldering to the pins of the DB9M plug which connects all three leads to CON1.

At the other end of each lead, remove 10mm of the outer sleeve, then cut away the screening braid wires as close as possible to the cut end of the sleeve. Then remove about 6mm of the inner insulation and finally tin the exposed conductors.

Separate the two halves of the figure-8 cable by about 30cm, then slip a 15-20mm length of heatshrink tubing over the two halves and solder 26mm insulated alligator clips to the exposed wires.

These small insulated alligator clips are the easiest way to make contact with typical commercial EEG electrodes, which are fitted with a small contact stud on the top.

Commercial electrode leads have a special matching clip for these studs but small alligator clips make a good substitute. Slide the pieces of heatshrink up and over the bases of the alligator clips and shrink them down.

This will give you the six shielded leads (in three pairs) needed to connect the main electrodes to the *Brainwave Monitor*. But a seventh lead is needed as well – the one for the ground reference or 'Cz' electrode.

This doesn't need to be shielded, so you can make it using a 1.2m length of light-duty insulated hookup wire. Just strip the insulation from about 6mm at each end and tin the ends of the wire. Solder the seventh alligator clip to one end of this wire.

The final step is to solder the tinned ends of all of these leads to the appropriate pins of the DB9M plug, as shown in Fig.5.

Note that the inner conductors of each shielded lead go to pins 5, 9, 4, 8, 1 and 6, while their shield braid wires all connect to pins 2, 3 or 7, along with the wire of the ground reference lead.

Obtaining EEG electrodes

There are numerous EEG electrodes available via a number of suppliers on eBay at reasonable prices.

Many of these are cup-shaped devices about 10mm in diameter with a connection stud at the top, made from either gold-plated metal or conductive plastic. Some of them have a flat base for contact with the scalp, while others have a double-hexagon array of tiny feet. Typical samples are shown in the photo above.

Some of these electrodes are intended for wet use, with a smear of conductive gel under the cup to ensure good electrical contact with the scalp. Others are intended for dry use, relying purely on physical pressure to make the contact.

Another type of EEG electrode you'll find is a smaller version of the self-adhesive electrodes intended for ECG use (ie, monitoring the electrical activity of the heart).

These have a dob of conductive gel inside a sticky ring, with a peel-off film over them both.

All you need to do with these electrodes is peel off the protective film and then apply the electrode to the right position on the subject's scalp.

These electrodes all share the same problem – they have a tendency to move or fall off if simply placed on the scalp; especially the dry types. If you search the internet, you'll find various kinds of skull caps which are designed to hold the electrodes in position.

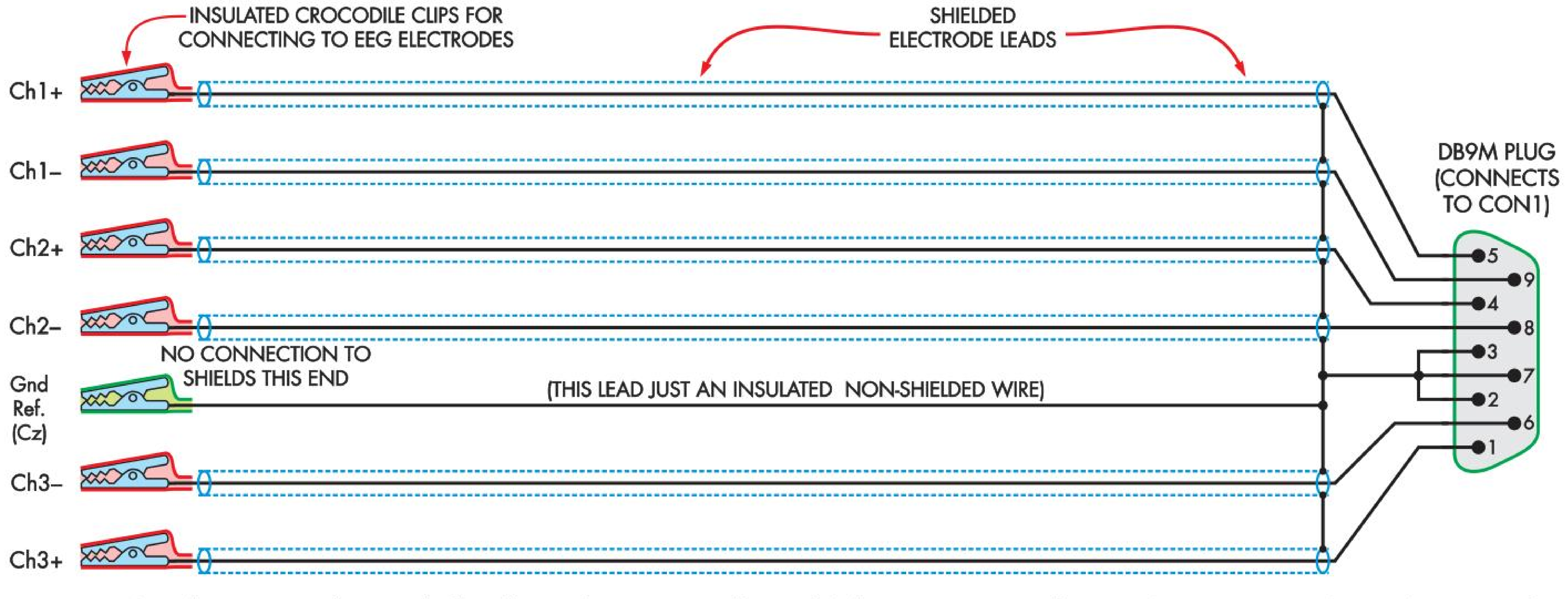

INSULATED CROCODILE CLIPS FOR CONNECTING TO EEG ELECTRODES
SHIELDED ELECTRODE LEADS
Ch1+
Ch1–
Ch2+
Ch2–
NO CONNECTION TO SHIELDS THIS END
Gnd Ref. (Cz)
(THIS LEAD JUST AN INSULATED NON-SHIELDED WIRE)
Ch3–
Ch3+
DB9M PLUG (CONNECTS TO CON1)
5
9
4
8
3
7
2
6
1

Fig.5: How to wire the seven electrode leads to the DB9M plug which connects to the *Brainwave Monitor's* input socket CON1. Note that apart from the Ground Reference (Cz) lead, all of the other leads should be shielded. The shields of all leads at the crocodile clip ends are left open circuit (only the internal wire is connected to the crocodile clips).

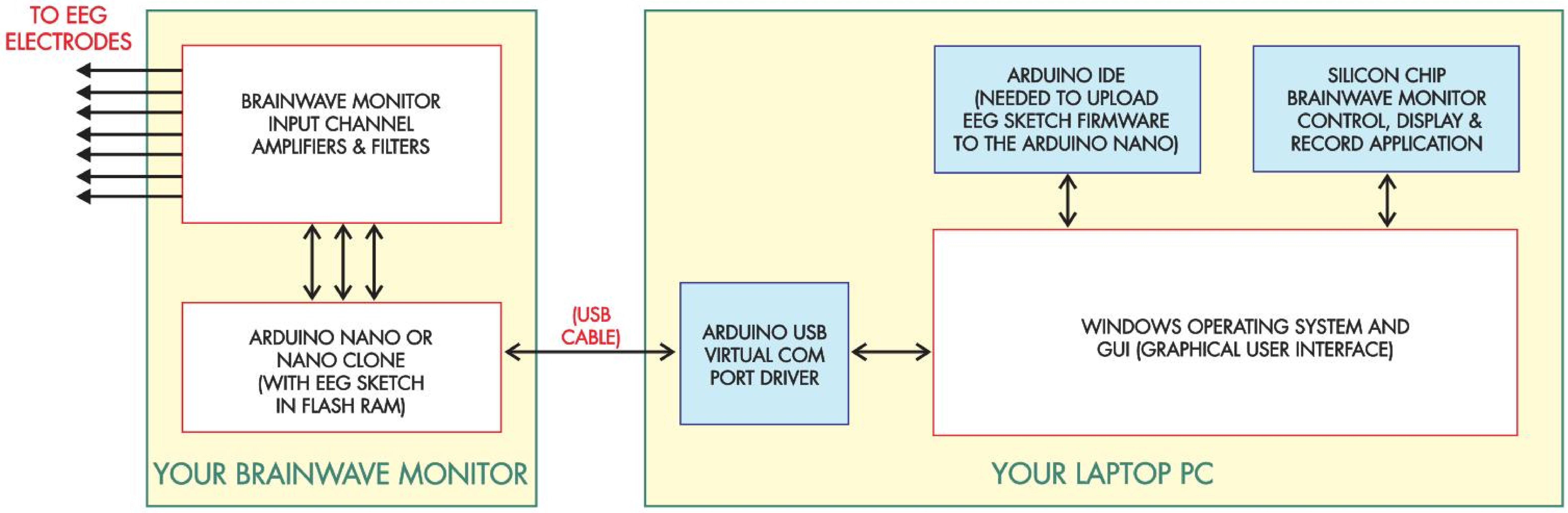
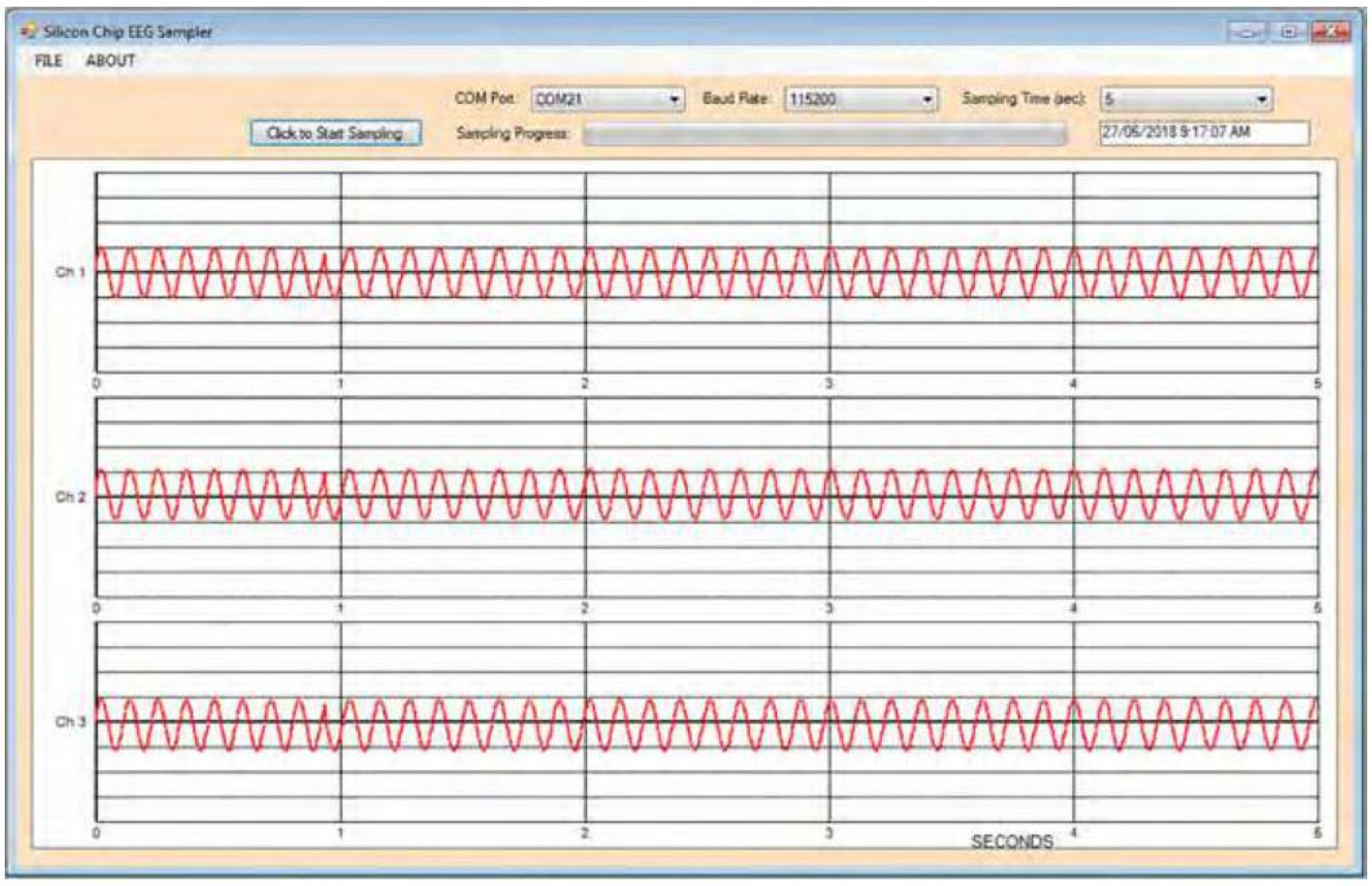

TO EEG ELECTRODES
BRAINWAVE MONITOR INPUT CHANNEL AMPLIFIERS & FILTERS
ARDUINO NANO OR NANO CLONE (WITH EEG SKETCH IN FLASH RAM)
YOUR BRAINWAVE MONITOR
(USB CABLE)
ARDUINO USB VIRTUAL COM PORT DRIVER
ARDUINO IDE (NEEDED TO UPLOAD EEG SKETCH FIRMWARE TO THE ARDUINO NANO)
SILICON CHIP BRAINWAVE MONITOR CONTROL, DISPLAY & RECORD APPLICATION
WINDOWS OPERATING SYSTEM AND GUI (GRAPHICAL USER INTERFACE)
YOUR LAPTOP PC

Fig.6: A block diagram showing how the 'software' side of the *Brainwave Monitor* works. On the left are the modules inside the *Brainwave Monitor*, while on the right are the functions inside your laptop/notebook PC.


Silicon Chip EEG Sampler
FILE
ABOUT
Click to Start Sampling
Sampling Progress:
Ch 1
Ch 2
Ch 3
0
1
2
3
4
5
SECONDS

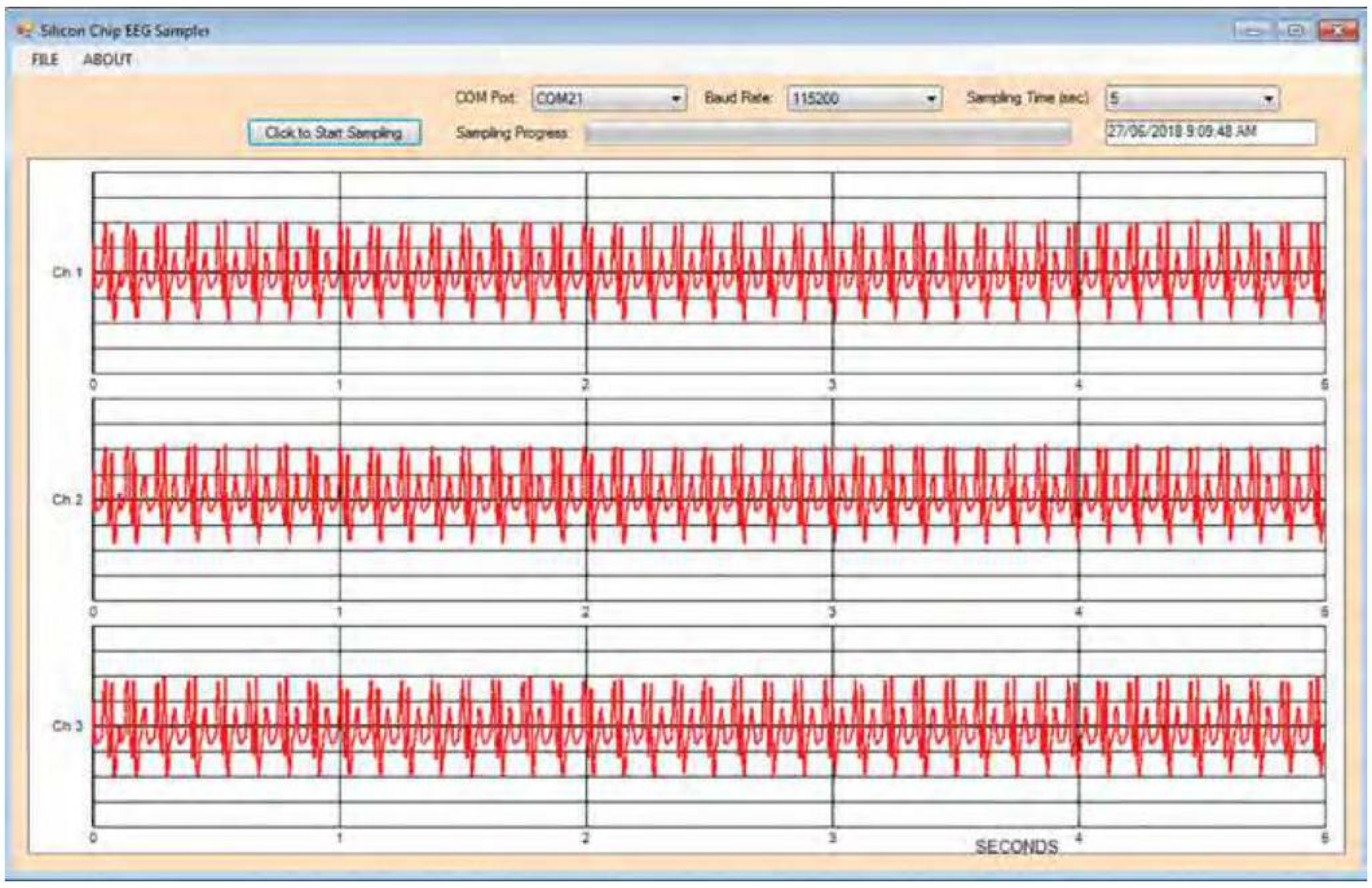
COM Port: COM21

Baud Rate: 115200

Sampling Time (sec): 5

27/06/2018 9:17:07 AM

Fig.7: a screen grab taken during early testing, with an 8Hz 75µV sinewave signal from a function generator applied to all three channels.


Silicon Chip EEG Sampler
FILE
ABOUT
Click to Start Sampling
Sampling Progress:
Ch 1
Ch 2
Ch 3
0
1
2
3
4
5
SECONDS

COM Port: COM21

Baud Rate: 115200

Sampling Time (sec): 5

27/06/2018 9:09:48 AM

Fig.8: another grab showing an 'ECG waveform' from the function generator applied to all three channels, again during early testing.

One of the most common types is an open grid made from elastic tubing, with small plastic ties at each intersection and a larger coupling piece down each side to allow attachment of an adjustable length strap passing under the lower jaw.

It looks quite weird, but should stop the electrodes from moving. You would first fit it over the subject's head, then slip the various electrodes under the grid in the desired positions

These caps are available at fairly low cost (around £5-£10 each) but you also have the option of using an old-fashioned elastic rubber or plastic shower cap, which would be much cheaper.

You could mark the outside of the shower cap with the 10/20 electrode reference grid and punch holes in the appropriate positions to hold the various electrodes in place, with their connection studs protruding to allow the clips to be connected.

Taking an EEG

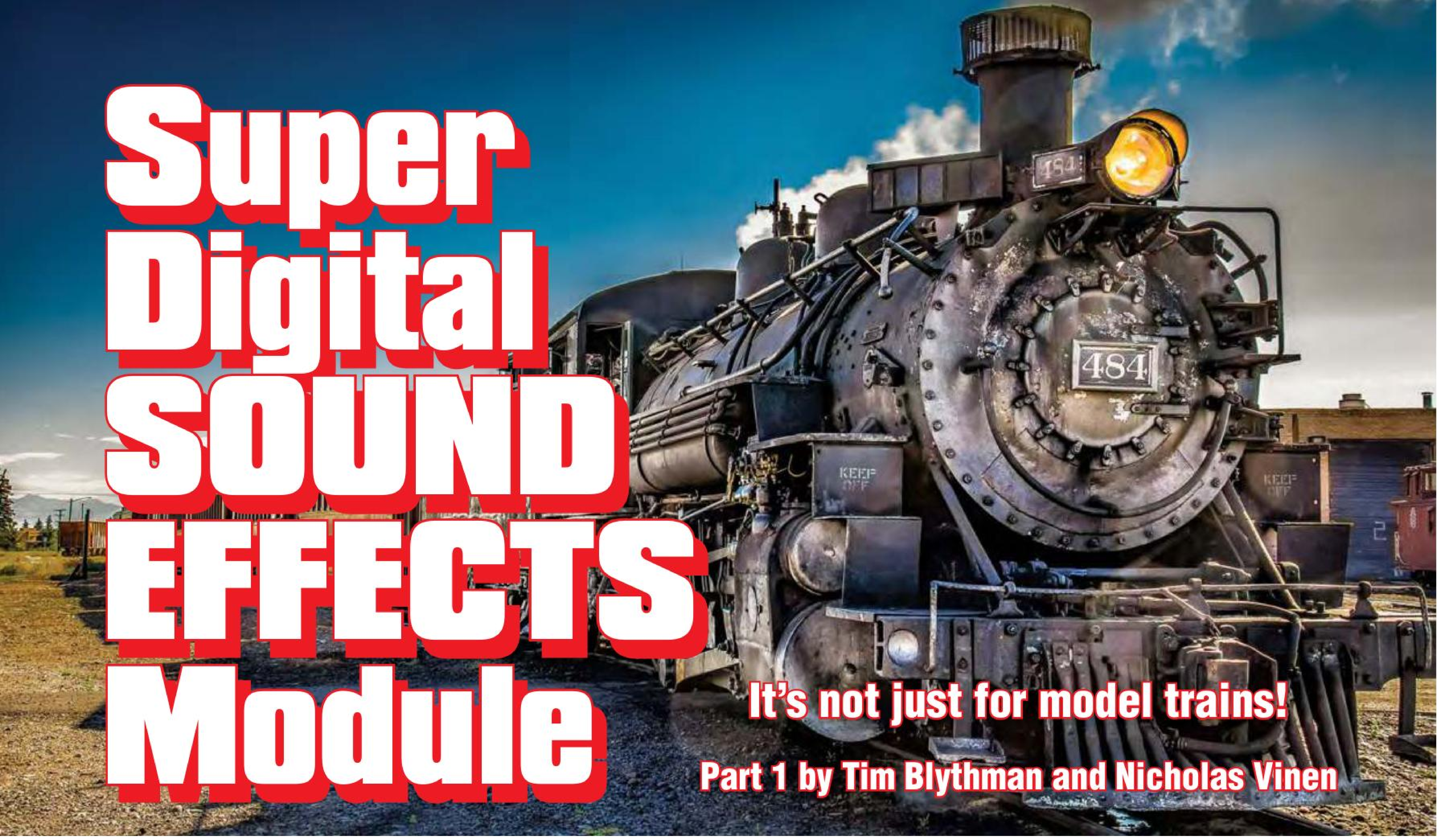
Apart from the gain of the input amplifiers, all other functions of the *Brainwave Monitor* are controlled using the software.

This is very easy to use because when you fire it up, it provides a GUI window (see screen grabs; Figs.7 and 8) which provides combo-box buttons along the top so you can set the sampling configuration: the COM port to which the sampler is connected, the Baud rate to be used (normally 115,200) for communication and the sampling time you want (5, 15, 30 or 60 seconds).

Then you start taking an EEG recording simply by clicking on the Start Sampling button.

During the sampling time, progress is shown by a progress bar along the top, plus the sample plot displays growing in the graph graticules.

As you can see there are two drop-down menus at the top, with the familiar labels 'File' and 'About'. The first menu gives you options for saving, reloading or printing your EEG recordings and also for closing the application when you're finished. The second menu is merely to display a small dialog box showing the version number of the software.



Super Digital SOUND EFFECTS Module

It's not just for model trains!

Part 1 by Tim Blythman and Nicholas Vinen

This powerful module can be loaded with dozens of sound effects or audio tracks, short or long, and boasts virtually unlimited playback time and advanced controls.

You won't believe that such a tiny board (just 58 × 24 × 7mm *including* the microSD card) could give such spectacular performance and versatility. It's so tiny it can fit inside really small spaces, such as the inside of a model locomotive (hint?!).

But despite its size, the the *Super Digital Sound Effects Module* (*SDSEM*) is feature packed, with the ability to read and play back a large number of WAV files from an SD card, including the ability to play several simultaneously (digitally mixed together).

It has advanced sound looping support, the ability to speed up and slow down playback and the ability to select from multiple sounds for a single input, round-robin style or randomly. The sample length can range from a fraction of a second to many hours.

It is obviously ideal for model railway sound effects (not only can it fit inside HO-scale [and larger] locomotives, but it can also be triggered by a DCC decoder). For example, you could set up one channel to provide start-up and shut-down engine sounds when the loco starts and stops moving, and also a sound that changes in pitch with the speed of a wheel.

You could then have other channels which overlay the engine sound with a horn, the sound of brakes squealing, an announcement or just about anything else you can think of or need. Plus, because it operates from a very wide supply voltage (5.5-18V DC or even a pair of AAA or AA batteries) there are arguably no applications it can't handle.

However, its uses are much wider than model railway layouts; in fact, it suits just about any application where sound files are required. For instance:

- Triggering a sound effect when a door is opened or closed (a great one for Star Trek fans!)
- Part of a child's toy
- Make a novelty greeting card
- Make announcements in an elevator
- Part of a vending machine
- Audio guide or to play sounds for museum exhibits.

The possibilities are practically limitless. We're sure there's another two or 50 rolling around your head right now! Plus, it will, without any add-ons, directly drive an external 8Ω speaker with its inbuilt 1.2W audio amplifier –and the sound is great.

If a speaker is too thick for any particular application, the *SDSEM* can drive a piezo transducer (although, of course, the sound quality will not be anywhere near as good). The sounds can be triggered by switches, relays or the outputs of a microcontroller.

Compare this to commercially available sound effects modules for a model locomotive. These typically cost over £50, and while they include engine sounds, horn or whistle sounds, brake sounds and others depending on the model, they're most unlikely to have the versatility or features this module offers.

Shown here life size, the *Super Digital Sound Effects Module* (*SDSEM*) is tiny enough to fit just about anywhere.

How it works

The basic circuit arrangement is shown in the block diagram, Fig.1. The *SDSEM* is based on PIC32 microcontroller IC1, which reads ordinary WAV files from the microSD card and plays them back when triggered via one of its digital inputs.

Once the audio data has been read off the SD card and processed, it is then fed to I^{2}S-input digital-to-analogue converter (DAC) IC2 and then to the 1.2W audio amplifier chip (IC3), which

Check out these features and specifications!

- 16-bit digital-to-analogue converter with 47kHz sampling rate
- Onboard 1.2W audio amplifier capable of directly driving an 8Ω speaker
- MicroSD card slot for sound storage (some built-in sounds provided)
- Four-channel audio mixing
- Multiple sound looping options, including 'attack-sustain-release' mode
- Seven digital trigger inputs, triggered on a low or high level
- Each input can trigger one/many sounds (round-robin / randomly selected)
- Variable playback speed option, based on an analogue voltage or pulse rate
- Plays 8-bit or 16-bit WAV files with sampling rates of 1-64kHz
- Supports mono or stereo PCM (uncompressed) files; stereo files are down-mixed to mono
- Two supply options: 2.0-3.6V battery or 5.5-18V DC input
- Very-low idle current (<10µA when battery powered, <1mA from DC input)
- Typical power consumption while operation: ~40mA (depends on volume, speaker type)
- Typical start-up delay: <0.5s from sleep mode, <0.1s from idle mode
- Based on a low-power PIC32 running at 24MHz
- Onboard error/activity LED
- Configured via text file on microSD card

can drive a small (or large) speaker or a piezo transducer.

There are two power supply options shown in Fig.1, one for a nominally 3V battery and one for a 5.5-18V DC supply; there will be more details on these options later.

The *SDSEM* is not just limited to simply playing one of seven sounds. By means of a simple text-based configuration file that is saved on the card, the operation of each of the seven trigger inputs can be customised to play back one of several sounds or a series of sounds with separate volume and mode configurations for each input.

While the sounds themselves are important, the way they are played back and mixed greatly adds to the effect. This module has eight different playback styles that can be configured, incorporating multiple sounds for each input.

For example, a horn or whistle sound typically rises in volume, maintains a level, then fades away slowly. One of the inputs on the *SDSEM* can be set up to provide this effect. We can create three separate sound files: one for the rising part, one for the steady part, and one for the fade. When the appropriate input is pulled low, the rising level sound plays. While the input remains low, the steady sound is repeated as often as necessary, and finally, the fading sound is played when the input is released.

This mode is called 'ASR' (attack, sustain, release) – the three phases of the overall sound effect. This style also suits generating sound effects for equipment such as compressors and dynamic brakes, which all have a characteristic ramp-up, hold and fade-away sequence.

Engine sounds are usually heard continuously, and there is an option to loop a sound as long as an input is triggered, or to alternate this with another sound that loops while the input is not triggered. There is also an option for a sound to play once when triggered, which is perfect for announcements and other one-off effects such as coupler clash or guard's whistle.

There are two more options, similar to the loop and single modes. They more or less work in the same fashion, but if the input is released during playback, the sound stops immediately.

If one sound is triggered while another is still playing, normally they will be mixed together so that you hear them simultaneously. But this can lead to volume overload and distortion. So each trigger input can specify a playback volume for the associated sounds, adjusted over a range of 256 steps. This allows the right balance of sounds to be set up. There is also a master volume setting which affects all sounds.

The unit is configured through a file on the SD card, which lets you easily combine the many available options to suit your particular application, whatever it might be.

For example, a single WAV file running in 'cropped single' mode is ideal for a custom birthday card powered by a battery, as the sound will only play once when triggered and will stop when the card is shut, preventing unnecessary battery drain.

The use of up to seven WAV files in single or looped playback mode can provide seven custom voice prompts or warning sounds controlled by separate triggers. These could even include DTMF tone sequences (there are online DTMF tone generators available) which automatically dial a preset phone number, with the unit's output fed into a telephone line through an appropriate coupling method.

It isn't even necessary to have more than one WAV file on the card to use all the inputs. Each input can be set to use the same WAV file in different modes or at different volumes. We'll go into the detail of what each of these modes does and how they are set up later on.

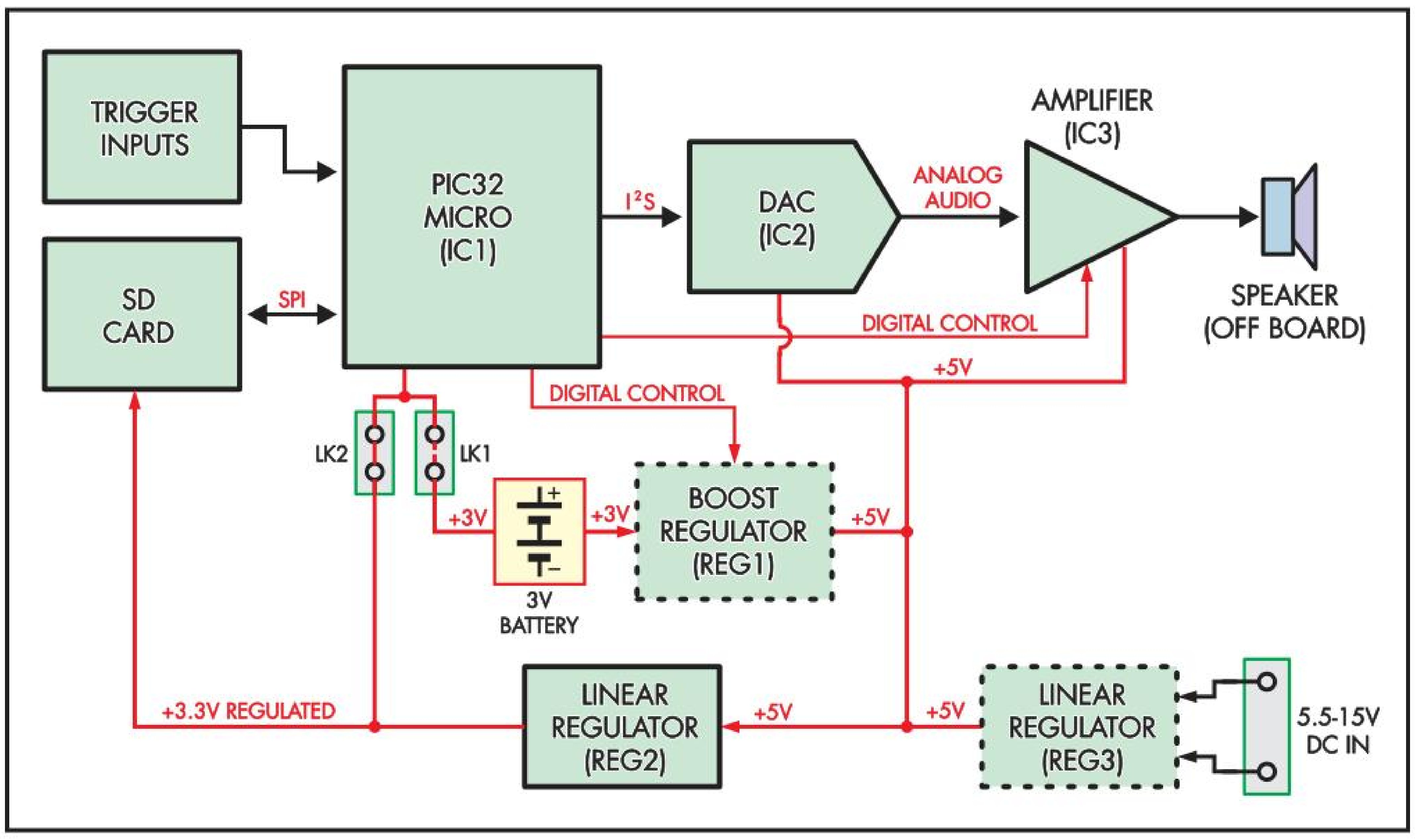


Fig.1: this shows how PIC32 microcontroller IC1 communicates with a microSD card using one of its two hardware SPI interfaces. The other is configured in I²S mode and drives the DAC, IC2.

General operating concept

The circuit diagram, Fig.2, shows the overall configuration of the *SDSEM*.

At its heart is PIC32MM0256GPM028 microcontroller IC1, featuring 256kB of Flash program storage and 32kB of RAM. The combination of a 32-bit processor and ample RAM is essential to the effective sampling and mixing required by this project.

The PIC32MM series is designed for compact low-power applications and runs at only 24MHz from an internal fast RC oscillator (8MHz), with the oscillator's output multiplied by a PLL (phase-locked loop). The large Flash storage space allows us to fit the required software, along with a few 'bonus' samples which can be used without an SD card inserted.

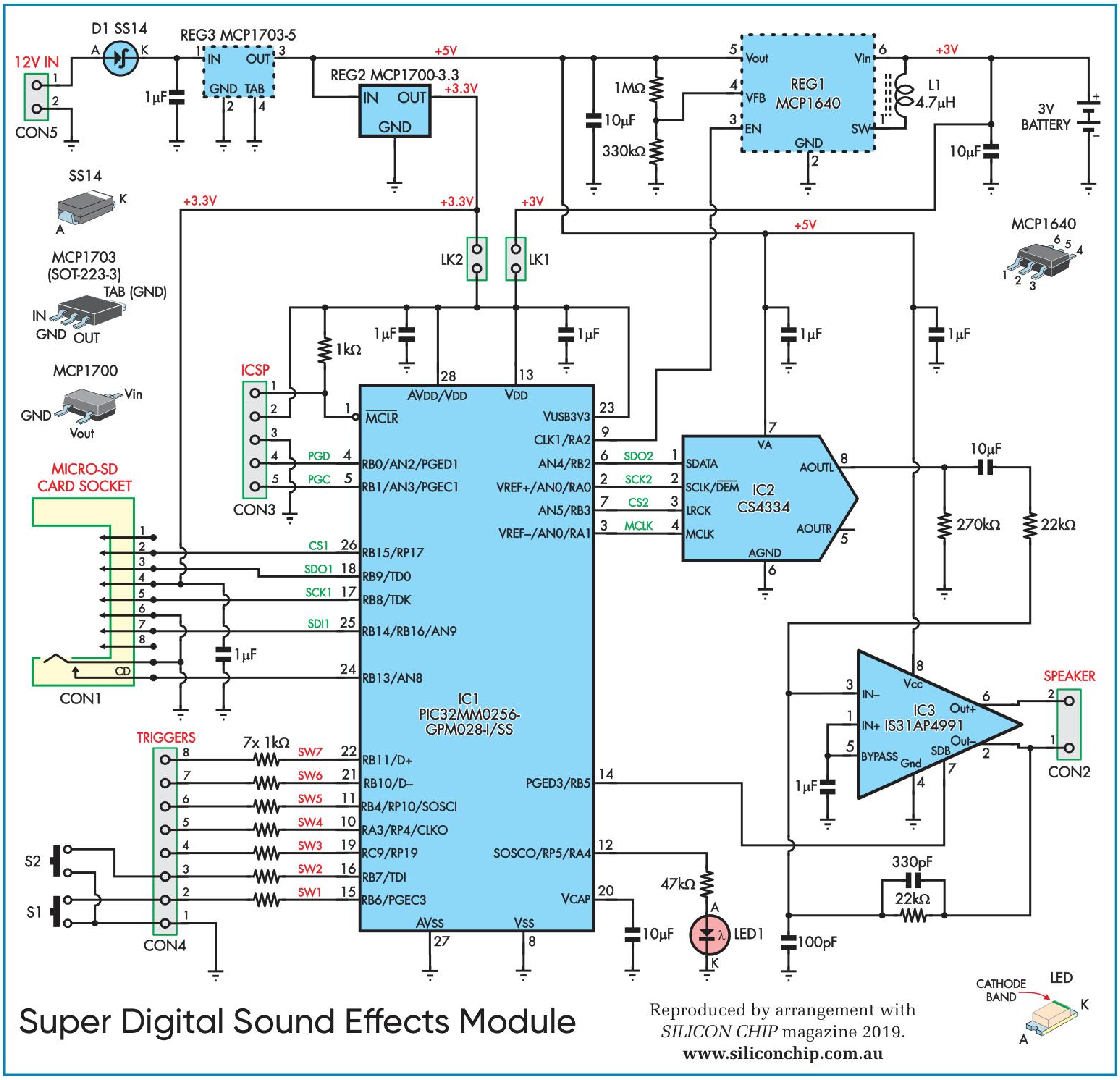
The PIC communicates with an SD card inserted into micro socket CON1 using one of its two hardware SPI ports. Besides the four usual SPI lines (clock, data in, data out and select), there is just one additional connection to the SD card socket, allowing the micro to sense the state of its 'card detect' microswitch.

This pin is shorted to ground when a card is inserted and is otherwise open circuit. An internal pull-up current is enabled by the software in IC1, which holds this pin high when the card detect switch is open, allowing the software to read the digital pin state and determine whether a card is present.

Once the audio data has been read off the SD card and processed by the micro, it is fed to a stereo digital-to-analogue converter (IC2, CS4334). The sound effects module operates in mono but most good-quality audio DACs are stereo, so we simply feed the chip identical data for each channel (this is a hardware option on the micro) and use just one of the DAC's outputs (AOUTL) at pin 8.

The audio from this pin is fed to a mono bridged amplifier IC (IC3, IS31AP4991). The audio signal is AC-coupled with a 10µF capacitor as the DC bias levels of the DAC and amplifier will not necessarily be the same (although they will both be similar, at around 2.5V).

The signal also passes through a 22kΩ series resistor which forms a low-pass filter with the two capacitors connected to IC3's pin 3 inverting input, as well as setting the bridged amplifier gain to two times, as it is the same value as the 22kΩ resistor from the pin 2 output back to the inverting input.


D1 SS14
A
K
12V IN
1
2
CON5
REG3 MCP1703-5
IN
OUT
GND
TAB
+5V
1µF
REG2 MCP1700-3.3
+3.3V
1MΩ
10µF
330kΩ
REG1
MCP1640
Vout
VFB
EN
GND
Vin
SW
+3V
L1
4.7µH
3V
BATTERY
SS14
MCP1703
(SOT-223-3)
TAB (GND)
GND
OUT
MCP1700
Vin
Vout
MCP1640
LK2
LK1
1kΩ
ICSP
PGD
PGC
CON3
MICRO-SD
CARD SOCKET
CD
CON1
CS1
SDO1
SCK1
SDI1
MCLR
RB0/AN2/PGED1
RB1/AN3/PGEC1
RB15/RP17
RB9/TDO
RB8/TDK
RB14/RB16/AN9
RB13/AN8
AVDD/VDD
VDD
VUSB3V3
CLK1/RA2
AN4/RB2
VREF+/AN0/RA0
AN5/RB3
VREF–/AN0/RA1
IC1
PIC32MM0256-
GPM028-I/SS
PGED3/RB5
SOSCO/RP5/RA4
VCAP
AVSS
VSS
SDO2
SCK2
CS2
MCLK
SDATA
SCLK/DEM
LRCK
VA
AOUTL
AOUTR
AGND
IC2
CS4334
270kΩ
22kΩ
IN–
IN+
BYPASS
Gnd
SDB
Vcc
Out+
Out–
IC3
IS31AP4991
SPEAKER
CON2
TRIGGERS
7x 1kΩ
SW7
SW6
SW5
SW4
SW3
SW2
SW1
RB11/D+
RB10/D–
RB4/RP10/SOSCI
RA3/RP4/CLKO
RC9/RP19
RB7/TDI
RB6/PGEC3
S2
S1
CON4
47kΩ
LED1
330pF
100pF
CATHODE
BAND
LED

Super Digital Sound Effects Module

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Fig.2: compare this complete circuit diagram to the block diagram, Fig.1. Either REG1 or REG3 is fitted (not both) to provide the 5V rail which powers IC2 and IC3. The seven series resistors between IC1 and CON4 help to protect IC1 against damage from static electricity or voltages outside its normal operating range of 0-3V or 0-3.3V (depending on the supply option).

The 22kΩ series resistor and 100pF capacitor to ground form a low-pass filter with a –3dB point of 22kHz, reducing the sampling artefacts of the DAC. The 330pF capacitor across the 22kΩ feedback resistor also provides a low-pass filtering effect as well as helping to stabilise the amplifier and prevent oscillation.

A 1µF capacitor from pin 5 of IC3 to ground stabilises its half-supply reference, helping to prevent any noise which may be present on its supply rail from being injected into the amplified outputs. It also has a 1µF supply bypass capacitor close to the IC, to provide it with bursts of current during audio transients. IC3 drives the 8Ω speaker directly, which is connected to its bridge output pins 6 and 2, via pin header CON2.

The amplifier IC is capable of directly driving an 8Ω speaker to more than 1W, assuming the power supply is capable of delivering the current. Depending on how the circuit is powered, the supply may not be capable of delivering the required current of 250mA or more. In this case, a higher impedance speaker can be used, or a resistor can be connected in series with the speaker to limit peak currents; more on this later.

Alternatively, you can connect a piezo transducer in place of the speaker. The sound quality will not be as good but the efficiency is higher and the amplifier has no trouble driving such a load (which is capacitive).

Digital audio interface

We operate the DAC (IC2) with a sampling rate of 46.875kHz. This may seem like an odd value; more typical sampling rates would be 44.1kHz (as used for CDs) or 48kHz (as used for DVDs). The reason for the unusual value is that this is an integral fraction of the maximum clock speed of the microcontroller, IC1 (24MHz). Hence, it can easily be produced by the micro using one of its internal timers/counters.

The DAC IC requires a 'master clock' which is a multiple of the sampling rate and the multiple must be one of several fixed ratios supported by the IC, specifically, 128, 192, 256, 384 or 512 times. If we run the micro at the full 24MHz and choose the 512-times value for the master clock, that allows us to have a sampling rate of 46.875kHz (24MHz ÷ 512) and this is the one that we have chosen.

The other multiplier values give a higher sampling rate unless we lower the microcontroller clock speed, but that would then slow down its processing. So we decided that the values specified above were the best choices.

+12V
0V
Spkr
Trig
1k1k1k1k1k1k
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S2
Sound Effects Mk2
01107181
BAT1
718986
00996VIP
ICSP
1
S1

The reverse side of the *SDSEM* PCB has a few components fitted, including switches S1 and S2.

As well as the master clock signal, which is fed to its pin 4, IC2 expects 16-bit digital audio data in I^{2}S format fed to pins 1-3, where pin 1 is the audio data input, pin 2 is the bit clock (which runs at 32 times the sampling rate, ie, for two channels with 16 bits of data each) and pin 3 is the left/right clock which runs at the sampling rate and indicates when the left channel data is on pin 1 (LRCK low) and when it's the right channel data (LRCK high).

Microcontroller IC1 has specific hardware for generating digital audio signals, including I^{2}S format. It does this using one of its two hardware SPI (serial peripheral interface) units. I^{2}S is similar to SPI but there are a few minor differences, such as the need to generate the extra left/right clock output signal.

So the serial data (to pin 1 of IC2) and bit clock (to pin 2) are generated in virtually the same manner as they would be in SPI mode, from output pin 6 of IC1 (configured as SDO) and pin 2 (configured as SCLK) respectively.

Pin 7 of IC1 would normally be the SPI chip select (CS) output, but in audio mode this becomes LRCK.

The MCLK signal for IC2 is produced from digital output pin 3 of IC1, but does not come from the audio signal interface. Instead, this pin is configured as a PWM output using a timer derived from the micro's system clock. Since this same clock is used to generate the I^{2}S audio signal clocks, the signals are synchronised and the ratios are locked.

When the DAC is not being used and the micro is in sleep mode, then since the micro is no longer driving the MCLK and LRCK pins with square waves, IC2 automatically goes into a low-power sleep mode. The amplifier can also be put into a low-power mode by the micro pulling its shutdown input (pin 7) high. This is connected to digital output RB5 (pin 11) on IC1.

Trigger inputs

Sound effects are triggered when one of the digital input pins 2-8 on pin header CON4 change state; normally they are triggered by being pulled low, but this can be inverted with a software option.

Each of these pins connects to a digital input on the micro via a 1kΩ resistor. These are present to protect the microcontroller in case a voltage outside the range of 0-3V is applied to one of these pins; they limit the current through the micro's input clamp protection diodes.

Each of the micro's seven digital trigger inputs is configured by the software to be supplied with a small pull-up current which flows from V_{DD}. This holds those inputs high unless they are externally pulled low. Thus, pin 1 on CON4 is tied to ground so you can trigger the sound (in the default mode) by shorting pin 1 to one of the other pins.

This can also be done by an external switch, relay or transistor. If onboard tactile pushbuttons S1 and S2 are fitted, they can be used to trigger the first two sound effects channels.

Power supply

The power supply arrangement is a little complicated since it is designed to be set up for two different power sources: either a battery of around 3V (eg, 2 AA or AAA cells) or a 5.5-18V DC supply from a plugpack, model railway train tracks (DC or rectified and filtered AC) or the rectified and filtered output of a transformer or similar.

When powered from a ~3V battery, link LK1 is shorted and so the microcontroller (IC1) is powered directly off the battery. When in sleep mode, it draws a tiny amount of current (under 1µA) so this connection will not drain the battery.

Switching boost regulator REG1 is also fitted for battery use. When in sleep mode, the micro keeps this shut down by driving its pin 3 enable input low, from its RA2 digital output (pin 9). When that output goes high, the boost regulator is enabled and it produces 5V at its pin 5 output.

No external transistors or diodes are required since this is a synchronous regulator, with all switching done internally. This also maximises efficiency. The external components required are inductor L1, which is used as an energy storage device and to boost the voltage, 10µF ceramic input bypass and output filter capacitors and a 1MΩ/330kΩ resistive feedback divider which sets the output voltage to 5V.

The 5V supply then powers the DAC (IC2) and audio amplifier (IC3). IC2 requires a 5V supply while IC3 can operate from 2.7-5.5V but will have a greater output swing and thus better power delivery when operating at higher voltages.

This 5V supply is then reduced to a regulated 3.3V supply to power the microSD card by linear regulator REG3.

While boost regulator REG1 can work with an input supply as low as 0.65V, since IC1 is also powered from the battery this means the minimum operating voltage is 2.0V.

Typical microSD cards will accept signal levels down to 2.0V, although they require a minimum supply voltage of 2.7V, so the card should not be the limiting factor on the minimum operating battery voltage.

With REG1 shut down, the only components drawing power are IC1 and REG1, both of which have very low current demand in the sleep/shutdown state. Total standby current is just a few microamps. Note though that this has the disadvantage that the microSD card must be initialised immediately upon the device being triggered, which means there can be a delay in playing back the first sound. This can be reduced by either pre-buffering some sounds in RAM or by keeping the micro awake and the regulator active for some time after each trigger event, so it's ready to be re-triggered. We'll explain these schemes in more detail later.

Alternative power arrangement

If a higher supply voltage is available then boost regulator REG1 is not necessary and should not be fitted. Reverse polarity protection diode D1 and 5V linear regulator REG3 are fitted instead. The DC supply is connected to pin header CON5, and the 5V output of REG3 powers IC2 and IC3.

REG2 supplies 3.3V to the microSD card as before, but in this case LK2 is inserted rather than LK1, and so microcontroller IC1 also runs from the output of REG2.

With this supply configuration, the sleep current is higher because IC2, IC3, REG2 and REG3 are always powered; however, these are all capable of entering low-power sleep mode or have a low quiescent current.

The microSD card is also powered continuously; however, this is kept in a low-power standby state unless it is actually being used.

So the sleep-mode current with this power supply arrangement is higher than with a battery and depends on how much current the SD card draws in its idle state. IC2 draws around 45µA and an SD card is usually around 0.5mA in standby mode, for a total that's typically well under 1mA.

Note that REG3 is physically larger than the other regulators (in an SOT-223 package rather than SOT-23) and it is soldered to a solid copper plane. This is necessary since, at higher input voltages (eg, 12V), its dissipation could be substantial.

During sound effect playback, the circuit could draw more than 100mA and with a 12V input and 5V output, that's in excess of 0.7W of dissipation.

Software details

The software for this project is quite complex as it provides many different configurable features and does a lot of 'real-time' processing in order to read and play back multiple files with different sampling rates and looping options at the same time.

Practically all of the 32KB RAM is used to buffer samples from the microSD card and the spare Flash memory is filled with some useful audio samples as well.

Initialisation

On startup, the software performs a number of initialisation tasks. It needs to set the initial state of the LED drive pins, control pins for REG1 and IC3, and microSD card interface pins. Both internal SPI peripherals need to be set up because one is used for communication with the SD card and the other, with the DAC. They also have re-mappable I/O pins, so those need to be set to the correct external pins.

Since the only interrupt service routine used by the software is for feeding audio data to the DAC – and this should not be interrupted – the interrupt priority is set to the highest possible level.

Pin 3 is set up as a 12MHz clock output to provide the master clock (MCLK) for the DAC. This utilises the SCCP4 peripheral (single-ended capture/compare/PWM) with a prescaler of 1:1 and a period of two clocks (the system clock is 24MHz). The rising-edge register is set to zero and the falling-edge register to one, meaning that the output alternates on each clock pulse, giving a 12MHz square wave.

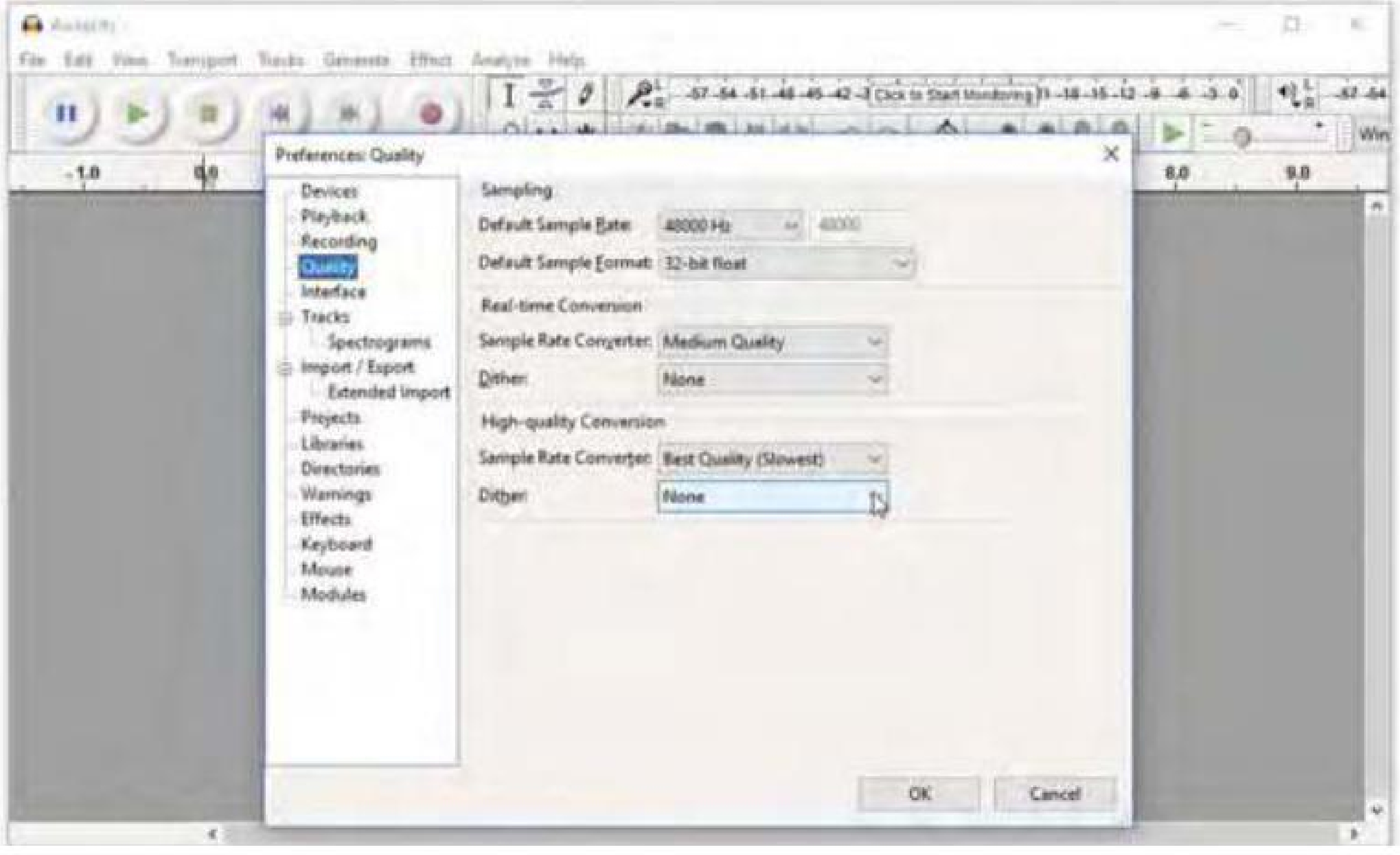
The microSD card requires power before it can be initialised, so as soon as the unit is triggered, the control pins for REG1 and IC3 are brought high to switch them on. The software then checks the level on the microSD card detect pin and flashes LED1 to indicate an error if it is not found. The card initialisation procedure then starts and once the card is ready, the configuration file is then found and loaded.

The configuration file consists of lines of text which are then 'parsed' one at a time, to extract the required settings, then stored in RAM to be referred to later.

Once that is complete, the interrupt which produces I^2S data for the DAC is activated and then the *SDSEM* is ready to operate.

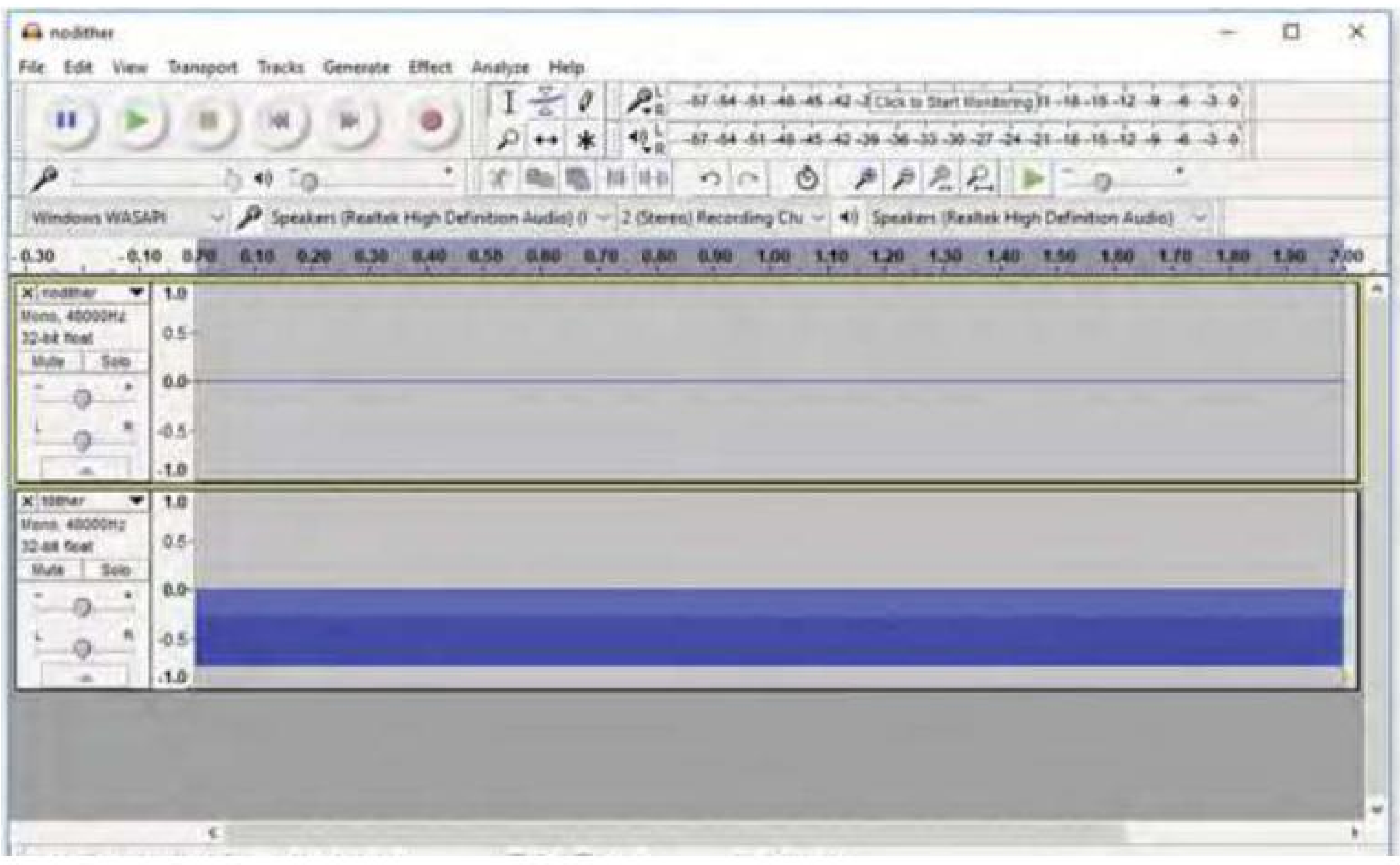
There are three 512-byte buffers for each of the four playback channels (ie, twelve buffers total). The interrupt service routine (ISR) checks whether there is any audio data to be played back, and if so, applies the appropriate volume for each channel and mixes the resulting samples.

The mixed sample value then has the master volume applied and is clipped to remain within the –32768 to +32767 range for 16-bit audio data.



Sampling
Default Sample Rate: 48000 Hz
Default Sample Format: 32-bit float
Real-time Conversion
Sample Rate Converter: Medium Quality
Dither: None
High-quality Conversion
Sample Rate Converter: Best Quality (Slowest)
Dither: None

It turns out that Audacity (by default) adds 'dither' to files as it saves them to spread out quantisation errors on downsampling. Unfortunately, the dither is audible, especially for 8-bit samples. To turn off dithering, select Preferences from the Edit menu, and set Dither on High-quality Conversion (here, High-quality Conversion means saving rather than playback) to none.


nodither
File Edit View Transport Tracks Generate Effect Analyze Help
Click to Start Monitoring
Windows WASAPI
Speakers (Realtek High Definition Audio)
2 (Stereo) Recording Ch
Speakers (Realtek High Definition Audio)
nodither
Mono, 48000Hz
32-bit float
Mute
Solo
dither
Mono, 48000Hz
32-bit float
Mute
Solo
1.0
0.5
0.0
-0.5
-1.0

You can see the difference by exporting a file of silence as 8-bit WAV before and after the change. Reopen the files (as we have done here, and amplify each by 40dB. The one without dither remains at zero, while the file with dither has an obvious hiss. 16-bit files also have dither applied, but the effects will not be as pronounced as the effects for 8-bit files.

Parts list
Super Digital SFX

1 double-sided PCB, coded 01107181, 55 × 23.5mm (available from the PE PCB service)
1 SMD microSD card socket CON1) [Altronics P5717 or similar]
2 mini SMD two-pin tactile pushbutton switches (S1,S2) (optional) [eg, Switchtech 1107G]
1 5-pin header (CON3) (optional, to program IC1)
1 speaker, size to suit (8Ω or greater) ***or*** piezo transducer (see text)
1 two cell AAA or AA battery holder (optional)

Semiconductors

1 PIC32MM0256GPM028-I/SS programmed with 0110718A.hex, SSOP-28 (IC1) (from PE website)
1 CS4334 16-bit stereo DAC, SOIC-8 (IC2)
1 IS31AP4991 mono bridged audio amplifier, SOIC-8 (IC3)
1 MCP1640 boost regulator, SOT-23-6 (REG1)*
1 MCP1700-3.3 LDO linear regulator, SOT-23 (REG2)
1 MCP1703-5 LDO linear regulator, SOT-223 (REG3)#
1 blue SMD LED, 3216/1206 package (LED1
1 1A schottky diode, DO-214AC (D1) [eg, SS14]#

# only required for 5.5-15V DC powered version

Capacitors

(SMD X7R ceramic, 6V, 2012/0805 size)
4 10µF
7 1µF 16V
1 330pF
1 100pF

Resistors

(SMD 1%, 2012/0805 size)
1 1MΩ
1 330kΩ
1 270kΩ
1 47kΩ
2 22kΩ
8 1kΩ
1 0Ω (LK1/LK2)

Inductors

1 4.7µH chip inductor, 3226/1210 size package, 1A+ (L1) [eg, Taiyo Yuden CBC3225T4R7MR]*

** only for battery-powered version*

If any clipping occurs, a flag is set which is picked up by the main loop and it operates to reduce the overall volume to limit distortion.

Main loop

With the DAC ISR handling audio output, the main program loop continues running. In addition to checking for the clipping flag, it also monitors each of the triplets of audio buffers. If one becomes empty and there is more data in the associated file, it fetches more data from the SD card to 'refill' the buffer. This way, the ISR never 'runs out' of audio data until it's time to stop playback.

After it fetches the data, it then re-samples that data (using linear interpolation) to match the DAC's sampling rate of 46.875kHz and also converts any 8-bit data to 16 bits, and stereo data is downmixed to mono.

The optimum WAV file format for use with this unit is 16-bit mono at 46.875kHz because this will not normally result in any re-sampling or downmixing. However, the use of 44.1kHz and 48kHz files will not result in much degradation.

Once it has ensured that all the audio buffers have data as required, the PIC then turns its attention to the seven digital trigger inputs. The behaviour of each input depends on the mode selected in the configuration file.

If it determines that an input has been triggered, it then checks if one of the four audio output channels is free. If so, the free channel is set up to play back the sound which has been configured to be triggered by this particular input. In doing so, it fills up that output channel's audio buffers before it actually starts playback, so that it will be able to fetch more data as they are emptied over time.

Once the buffers are empty and the source file(s) are exhausted, that channel is freed up for use by another sound-effect trigger in future.

If an input is set up with one of the 'attack-sustain-release' type configurations mentioned earlier then it is necessary to start playback of a second file once the first one has finished. In this case, as soon as the first file playback is finished and an audio buffer is free, the second file is opened and the audio buffer refilled. The same procedure happens once the 'sustain' sample has finished playback.

If an input is set up to play files in round-robin or random mode then multiple files can be specified for that input. In round robin mode, the first time the input is triggered, the first file is played back. The second time it is triggered, the second file is played back and so on until the last file is played back, at which point the sequence restarts.

In random mode, a pseudo-random number generator is used to select one of the listed files to play back each time that input is triggered. Each subsequent trigger event may therefore trigger the same sound again or a different sound; there will be no obvious pattern.

If there is no audio being played back, the main loop starts a timer.

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For more information or software download please visit
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Connect, Control
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Drive
- up to 256 microsteps
- 50 V / 6 A
- USB configuration
- Isolated
- up to 32 microsteps
- 30 V / 2.5 A
PoScope Mega1+
PoScope Mega50
Measure
- up to 50MS/s
- resolution up to 12bit
- Lowest power consumption
- Smallest and lightest
- 7 in 1: Oscilloscope, FFT, X/Y, Recorder, Logic Analyzer, Protocol decoder, Signal generator

Once that timer has reached a user-configured threshold, the unit goes into low-power sleep mode, powering down the SD card and anything else that's under the micro's control (including itself).

Because we are not writing anything to the microSD card, the file handles and configuration data can remain in RAM and do not have to be read off the card again, saving some time next time an input is triggered and the chip comes out of sleep mode.

Changing playback pitch

The trigger inputs connected to pins 5 and 6 of CON4 (ie, pins 10 and 11 of IC1) can also function as analogue inputs. So one feature of the software is the ability to reprogram either or both of these inputs as analogue voltage pins which control the playback speed and therefore pitch of the sounds triggered on other channels.

If enabled, the software periodically samples the voltages on the appropriate pin using IC1's internal analogue-to-digital converter (ADC) and then uses this to 'tweak' the sampling rate that's being used to play back the sounds for the configured channel.

For example, if we play it back at half of the actual sampling rate then the sounds will be one octave lower than normal (and will take twice as long to play back) while if we play it back at double the actual sampling rate, the sounds will be one octave higher and it will take half as long to play back.

In reality, the sampling rate shift is not normally this extreme, but it allows for engine sounds that change in pitch with speed and so on.

The trigger input connected to pin 4 of CON4 (ie, pin 19 of IC1) can function as the clock input for IC1's internal TIMER3 counter. This pin can be configured as a pulse counter input and the pulse rate (ie, frequency) can then be used to vary the sound playback rate.

Regardless of whether you are using an analogue voltage or a pulse frequency to vary the sound playback rate and pitch, you can specify on a per-channel basis which is the controlling input, the control range of the voltage or frequency and the percentage change in playback rate which results.

Audible debugging

Since the unit has no display and only one LED which can indicate just a few error conditions, we have also programmed the chip with an audible debugging mode. When enabled, it 'speaks' its settings via the audio output, so that you can check to see whether it has been configured the way you have intended.

We have implemented this feature by using speech synthesiser software to produce samples for all the necessary words and numbers and then these have been stored in the PIC's Flash memory.

So when you enable this mode (called 'speakback' in the configuration file) at power up, it will audibly list all of its settings and then you can listen to the output and see whether everything is as expected.

The only part of the configuration which isn't 'spoken' is the file names. Each file mentioned in the configuration file is checked to see if it appears to be valid (ie, the name refers to a file that's stored on the SD card) and it will then say 'OK' or 'not OK' depending on whether the file has been found or not. Otherwise, all configuration parameters are read out for you to check.

Once you're happy that the configuration is correct, you can edit the config file and switch this mode back off, to get normal operation.

Next month

In part two, we will get onto the fun section: putting it together and full instructions for setting up and using your new *SDSEM*.

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Farnell AP60/50	PSU 0-60V 0-50A 1kW Switch Mode	£300
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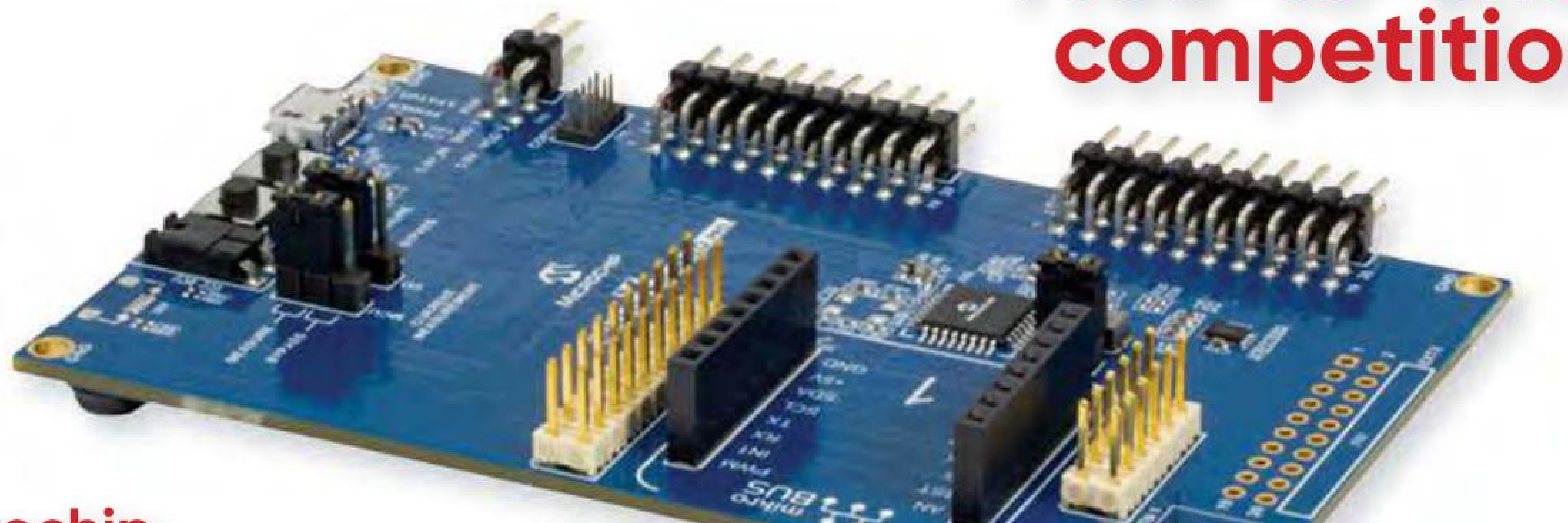

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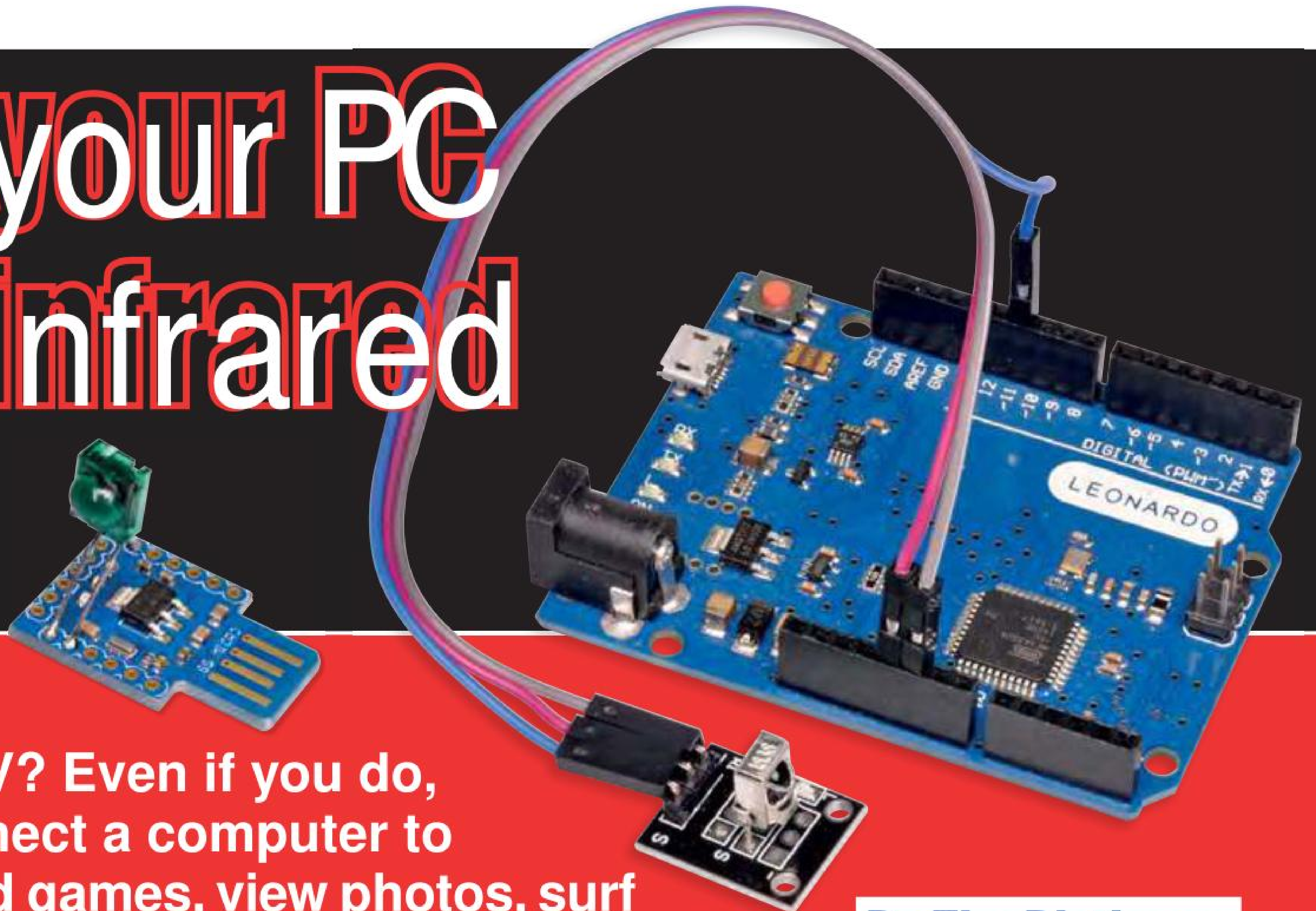
Control your PC with an infrared remote



Don't have a Smart TV? Even if you do, you may want to connect a computer to play videos, music and games, view photos, surf the web, and so on. This is known as a home theatre PC (HTPC). But operating a keyboard and mouse from the couch is clumsy. Why not use an infrared remote control for important functions like play, pause or next track? It's surprisingly easy to do!

By Tim Blythman

Like many tech-savvy people, I have a computer hooked up to my TV. I use it mainly for watching DVDs and YouTube on the big screen. I can even play games or surf the net. But if I'm watching a movie and I want to pause it, I don't want to fiddle with a wireless mouse or keyboard.

I have trouble with my wireless mouse since its range is only just good enough to reach from the couch to the TV, so it doesn't work reliably. And I often forget to turn it off after using it, prematurely flattening its batteries.

An infrared (IR) remote control is far better suited to that sort of task; and you probably already have many at hand that are likely to have some spare buttons that you could re-assign for various purposes. It's so much easier to just pick it up and press a button.

You may well have the parts needed to build this project. There's hardly any assembly required since it only involves two components. You can use it with a wide range of remote controls, including inexpensive generic programmable remotes.

How does it work?

If you're familiar with the Arduino Leonardo you might have an inkling as to how we achieve the computer interface. The Leonardo has a USB interface and it can be set up to appear, from the computer's point of view, as a USB keyboard and/or mouse. This is also true of other ATmega32U4-based Arduino boards; there are a few. We just need to arrange to receive IR commands and translate them into keystrokes or mouse movements/clicks.

The Leonardo remains attached to the computer's USB port (you can even use it with a Raspberry Pi) so it doesn't need any external source of power.

You might own an HTPC, like the ASUS PB40, or have built your own to use with a TV. While useful, it can be a pain to control using traditional means. That's why we've come up with a way to use a standard IR remote to control it.

The only difficulty is knowing what codes to expect from the remote control. For this, we can temporarily set up the Leonardo to tell us what codes it is receiving. We've done this with a remote control that's available from Jaycar so you can simply use the codes we provide and get the remote control up and running in minutes.

It sounds simple, but the devil is in the detail. What keystrokes do we need to emulate? And how do we send them?

Hardware

As we mentioned, we can use pretty much any ATmega32U4-based Arduino board, including the 'Leonardo' or the smaller 'Leostick' version that's available from Jaycar. If space is at a premium, there is a variant known as a 'Micro', and an even smaller (clone) version, which can be found under the name 'Beetle'. The Beetle isn't much bigger than most other USB dongles, so should fit just about anywhere.

A 3-pin IR receiver module is then attached to the Arduino board so we can receive the signals from our remote control.

Software

Fortunately, there are libraries available that already do most of the hard work for us. The first one (**github.com/z3t0/Arduino-IRremote**) is used to receive and decode the IR signals, giving us a different code for each button that's pressed on the remote control.

CHANNEL
CH-
CH
CH+
PREV
NEXT
PLAY/PAUSE
VOL-
VOL+
EQ
0
100+
200+
1
2
3
4
5
6
7
8
9
Car mp3

This remote control from Jaycar Electronics (XC3718) has 21 keys, each of which generates a different code based on the NEC IR protocol. The codes are detected and converted into keystrokes or mouse actions.

This is a great library that can also be used to transmit IR signals.

The two other libraries we're using allow us to emulate a keyboard (**github.com/arduino-libraries/Keyboard**) and a mouse (**github.com/arduino-libraries/Mouse**). The only remaining hard part is deciding which IR code corresponds to which action.

With most of the complex functions hidden in the libraries, our software sketch mainly deals with reading the codes from the IR receiver library and then feeding the appropriate actions to the keyboard and mouse emulation libraries.

Construction

There isn't much to the hardware so it makes sense to assemble it first. The hardware can be used for figuring out what code is generated by each remote control button, and then reused as the actual IR/keyboard/mouse interface. We built two prototypes using different Arduino modules, as follows.

A tiny Beetle

The Arduino Beetle variant is a minimal ATmega32U4-based board designed by DFRobot. Although it hasn't been around for long, it has been 'cloned' and these clones are available from many online stores. We don't even need to solder the supplied headers to it. We can simply solder the IR receiver straight to the pads on the board.

When complete, the final unit is smaller than most USB flash drives. The IR receiver's GND pin is soldered to the GND pad on the PCB, the V_{CC} pin to the 5V pad and the DATA pin to digital input D11. The IR receiver library can use any digital pin as the input, but this is the one that we have chosen.

The Beetle can just be plugged into a USB type-A port on a computer, as is.

Most IR receiver modules use the same pinout (eg, from Jaycar / Altronics) so you can most likely solder yours as shown here. But if you use a receiver from a different source, do double-check the data sheet. Looking at the lens from the front with the leads at the bottom, the pins from left-to-right are DATA, GND and V_{CC}.

If you like, you can carefully twist the receiver so that it will face the right way (towards the couch you are comfortably sitting on) when plugged into the computer. As long as the wires don't touch, you should have no troubles. Use heatshrink insulation if in doubt.

A larger variant

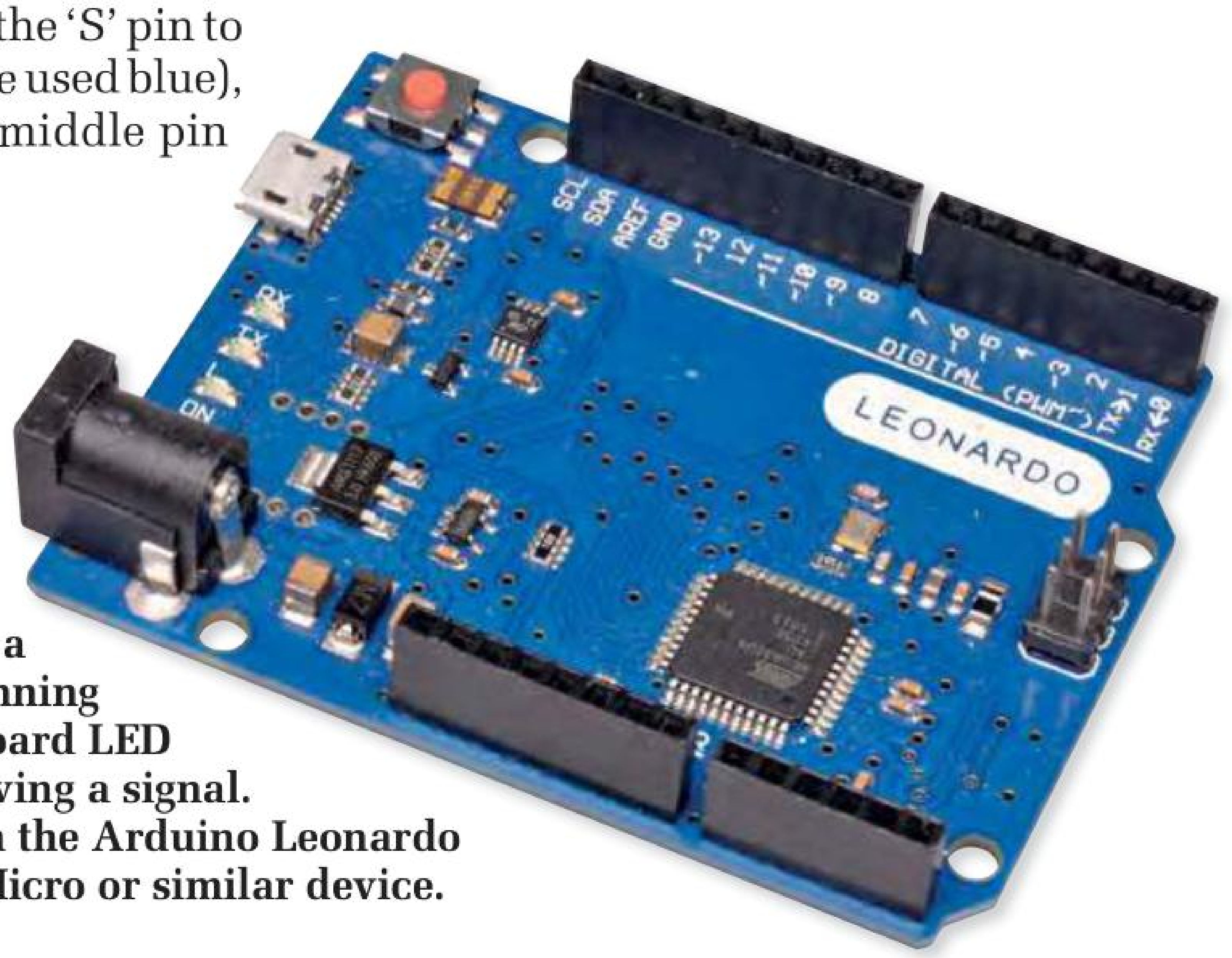
If you have an Arduino-compatible Leonardo or Micro board it is possible to put this project together without any soldering. Perhaps you just want to test that it does what you want before assembling something permanent.

In that case, we can use an Arduino-compatible module and some jumper leads to quickly put everything together. It may not be compact, but it will work just as well as the Beetle version.

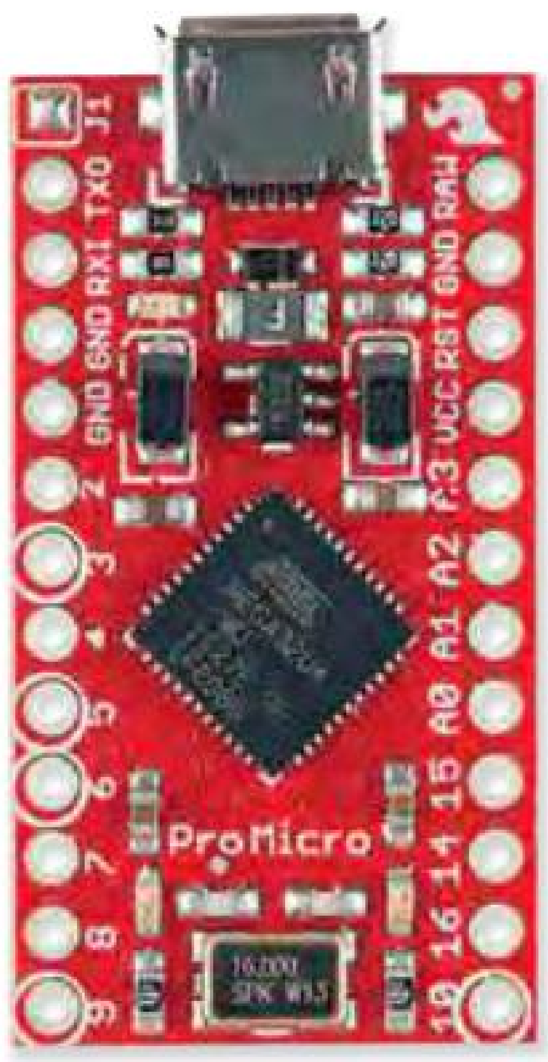
We also happened to have an IR receiver assembly that includes the actual receiver module plus an onboard LED. This means that you can easily see if it's receiving a signal.

If using such a module, check the markings on it to see which pins are which. They generally have an 'S' to identify the data pin and a '–' for the ground pin, with the unmarked middle pin being the positive 5V supply.

Run a jumper lead from the 'S' pin to D11 on the Leonardo (we've used blue), '–' to GND (grey) and the middle pin to 5V (violet).



This IR receiver module is a great way to get up and running quickly. It also has an onboard LED to indicate when it is receiving a signal. You can then pair this with the Arduino Leonardo shown right, an Arduino Micro or similar device.



There are a few variants of Arduino-compatible boards that will work with this project, like the ProMicro pictured. Compatible boards need to be based on the ATmega32U4 processor, which has a built-in USB interface.

Getting the codes

If you aren't using the Jaycar remote control, you will need to figure out which codes are produced by each button that you intend to use. We've written a brief sketch which looks for signals from the IR receiver and then types that code out on the PC using the emulated keyboard.

You can dump the codes into a spreadsheet or other document for use in our next step. Using a spreadsheet makes it easy to assign a name to each code for later reference.

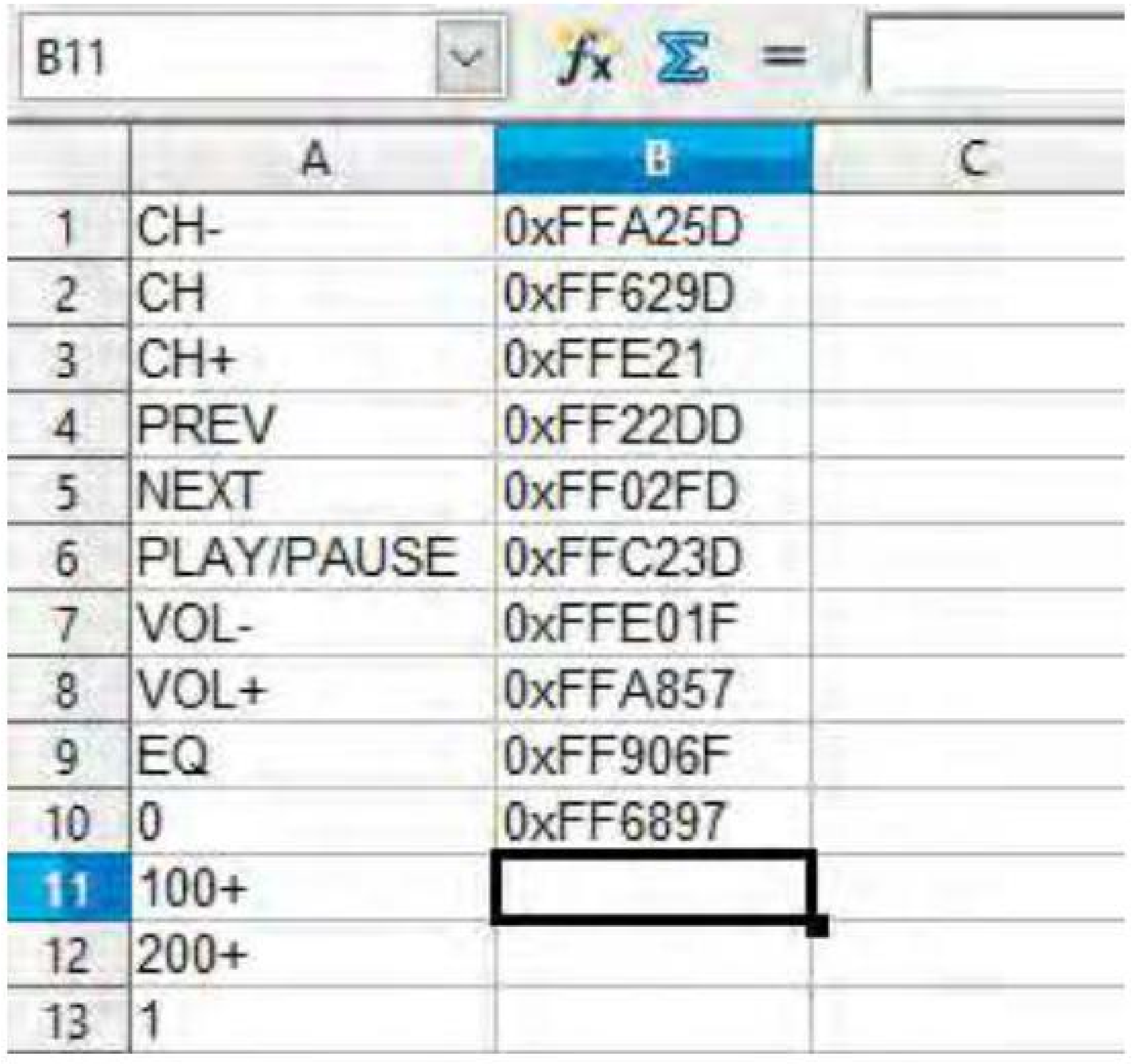
Keep in mind that the buttons you use on the remote shouldn't be used for anything else, even if the TV is in a different mode.

Otherwise, the TV and computer might both respond to the same button press, with unexpected results.

Finding out which key codes to generate

Having determined what button you've pressed on the IR remote, the Arduino code then needs to know which key or button press to generate in turn. This will depend on the software that you're running on the PC.

I use the VLC media player for watching videos on my HTPC. It's free and for the most part it just works. If you use a different player, it will probably have a different set of keyboard shortcuts, although most seem to use the space bar to play/pause. If in doubt, open your player of choice and mash away at the keyboard until you find out which key does what.



B11

	A	B	C
1	CH-	0xFFA25D	
2	CH	0xFF629D	
3	CH+	0xFFE21	
4	PREV	0xFF22DD	
5	NEXT	0xFF02FD	
6	PLAY/PAUSE	0xFFC23D	
7	VOL-	0xFFE01F	
8	VOL+	0xFFA857	
9	EQ	0xFF906F	
10	0	0xFF6897	
11	100+		
12	200+		
13	1		

Finding out the codes that an IR remote control uses is as simple as opening a spreadsheet program and loading our IR_Code_Typer.ino **sketch, which types the received codes directly into a spreadsheet.**

The commands that I wanted to use for VLC are: play/pause, toggle fullscreen mode, skip backwards and forwards. There's a great guide to all the shortcut keys at **https://wiki.videolan.org/Hotkeys_table/**

The keys I needed are in the first dozen listed, so this information was easy to establish.

The Jaycar remote control I used only has a single play/pause toggle button, so I had to settle for using the space key to toggle between play and pause. Toggling fullscreen involves simply pressing the 'F' letter key.

For skipping forwards and backwards, we have the choice between using very short, short, medium and long jumps.

According to the application's settings, a short jump is 10 seconds, which sounds like a good amount and is accessed using the Alt-Left Arrow or Alt-Right Arrow key combinations.

Sending keystrokes to a PC

The Arduino keyboard library is fairly easy to use. For example, to send the 'F' keypress for toggling fullscreen mode, we can simply use this line of code:

```
Keyboard.write('f');
```

It's almost as though we are printing a character to the serial monitor. But for key combinations like Alt-Left Arrow, it's not quite so easy.

There are two catches here. One is that we are sending a non-printing key (ie, the arrow key) and the second is that we're sending a key modifier (Alt).

This web page gives an overview of all the special keys: **www.arduino.cc/en/Reference/KeyboardModifiers**

This tells us that to send a Left Arrow keypress, we can use the following code:

```
Keyboard.write(KEY_LEFT_ARROW);
```

To send Alt-Left Arrow, we need to send the computer the correct key presses and releases in the correct order, with a slight delay, as that is how the computer is expecting to receive them (as though a real human was pressing the keys):

```
Keyboard.press(KEY_LEFT_ALT);
Keyboard.press(KEY_LEFT_ARROW);
delay(100);
Keyboard.releaseAll();
```

This is a bit involved but it gives us a lot of flexibility. For example, you could use the following code sequence to run any Windows program (in this case Notepad) using the WIN+R shortcut:

```
Keyboard.press(KEY_LEFT_GUI);
Keyboard.press('r');
delay(100);
Keyboard.releaseAll();
delay(200);
Keyboard.print("notepad");
Keyboard.write(KEY_RETURN);
```

If you're going to use a sequence like this, it's a good idea to test it individually before mapping it to an IR remote button, and remember, the computer may respond differently if a different program has the focus (ie, is in the foreground) when the sequence is activated.

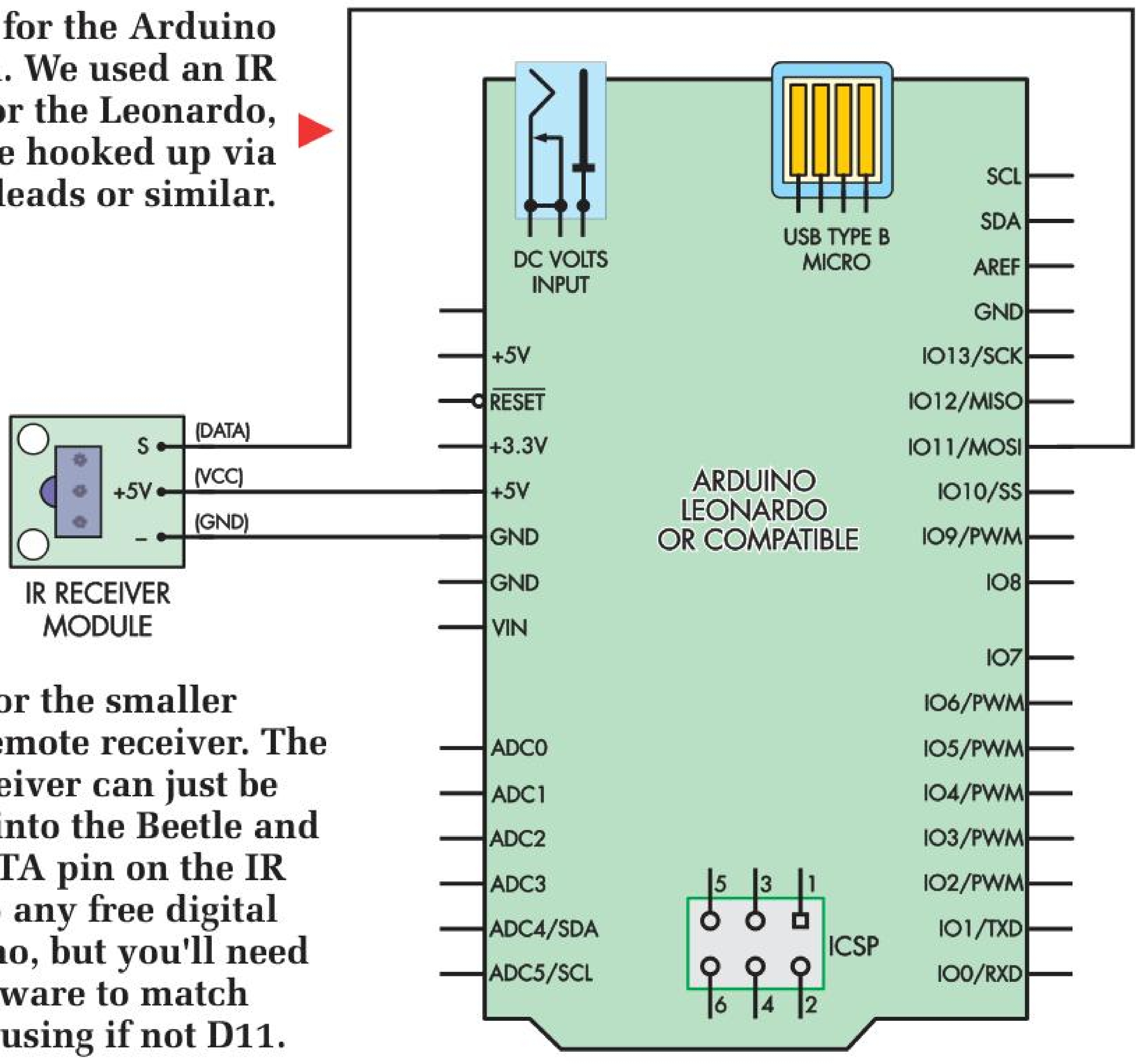
For sequences which start with a press of the 'Windows Key', like the one immediately above, this should not be a problem as they are captured by the operating system, regardless of which program is in the foreground. But it's also worth testing what happens if a certain keystroke occurs under a different program.

What about the mouse?

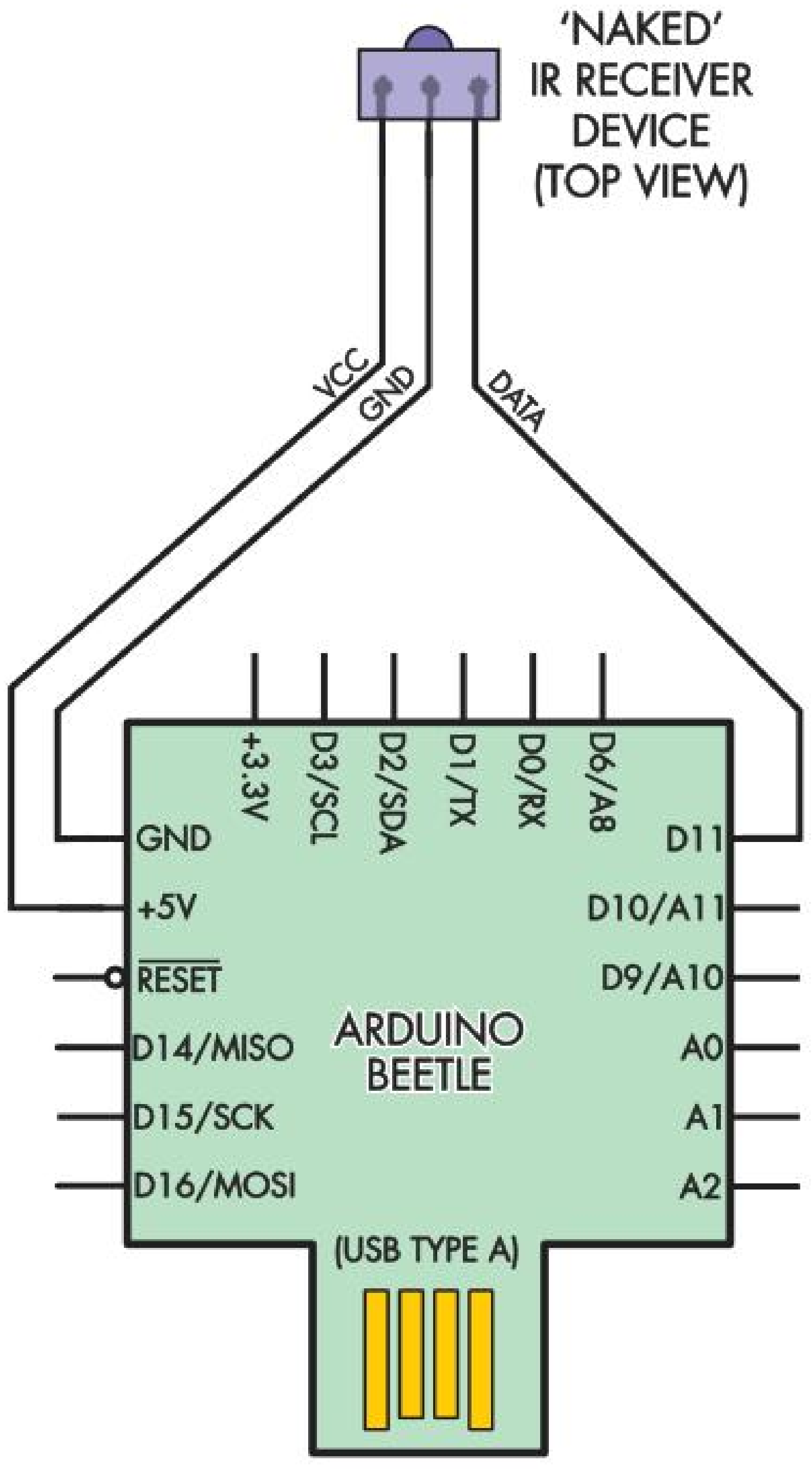
As we mentioned, there's also the possibility of emulating mouse movements and button presses. If you have a spare group of five or even nine buttons on the remote control, it's possible to use them to move the mouse cursor and click. The library provides two different functions to control the mouse. The simplest is:

```
Mouse.move(x,y);
```

This simply moves the mouse pointer in the x and y directions by the number of pixels specified. If x is negative, the


DC VOLTS INPUT
USB TYPE B MICRO
S
+5V
–
(DATA)
(VCC)
(GND)
IR RECEIVER MODULE
+5V
RESET
+3.3V
+5V
GND
GND
VIN
ADC0
ADC1
ADC2
ADC3
ADC4/SDA
ADC5/SCL
ARDUINO LEONARDO OR COMPATIBLE
SCL
SDA
AREF
GND
IO13/SCK
IO12/MISO
IO11/MOSI
IO10/SS
IO9/PWM
IO8
IO7
IO6/PWM
IO5/PWM
IO4/PWM
IO3/PWM
IO2/PWM
IO1/TXD
IO0/RXD
5
3
1
6
4
2
ICSP

Wiring diagram for the Arduino Leonardo version. We used an IR receiver module for the Leonardo, which can then be hooked up via flying leads or similar.


'NAKED' IR RECEIVER DEVICE (TOP VIEW)
VCC
GND
DATA
+3.3V
D3/SCL
D2/SDA
D1/TX
D0/RX
D6/A8
GND
D11
+5V
D10/A11
RESET
D9/A10
D14/MISO
A0
D15/SCK
A1
D16/MOSI
A2
ARDUINO BEETLE
(USB TYPE A)

Wiring diagram for the smaller Arduino Beetle remote receiver. The pins of the IR receiver can just be inserted directly into the Beetle and soldered. The DATA pin on the IR receiver can go to any free digital pin on the Arduino, but you'll need to change the software to match which pin you're using if not D11.

pointer moves left and if x is positive, the pointer moves right. Up is negative on the y-axis. To simulate a left-click, you can use:

```
Mouse.click();
```

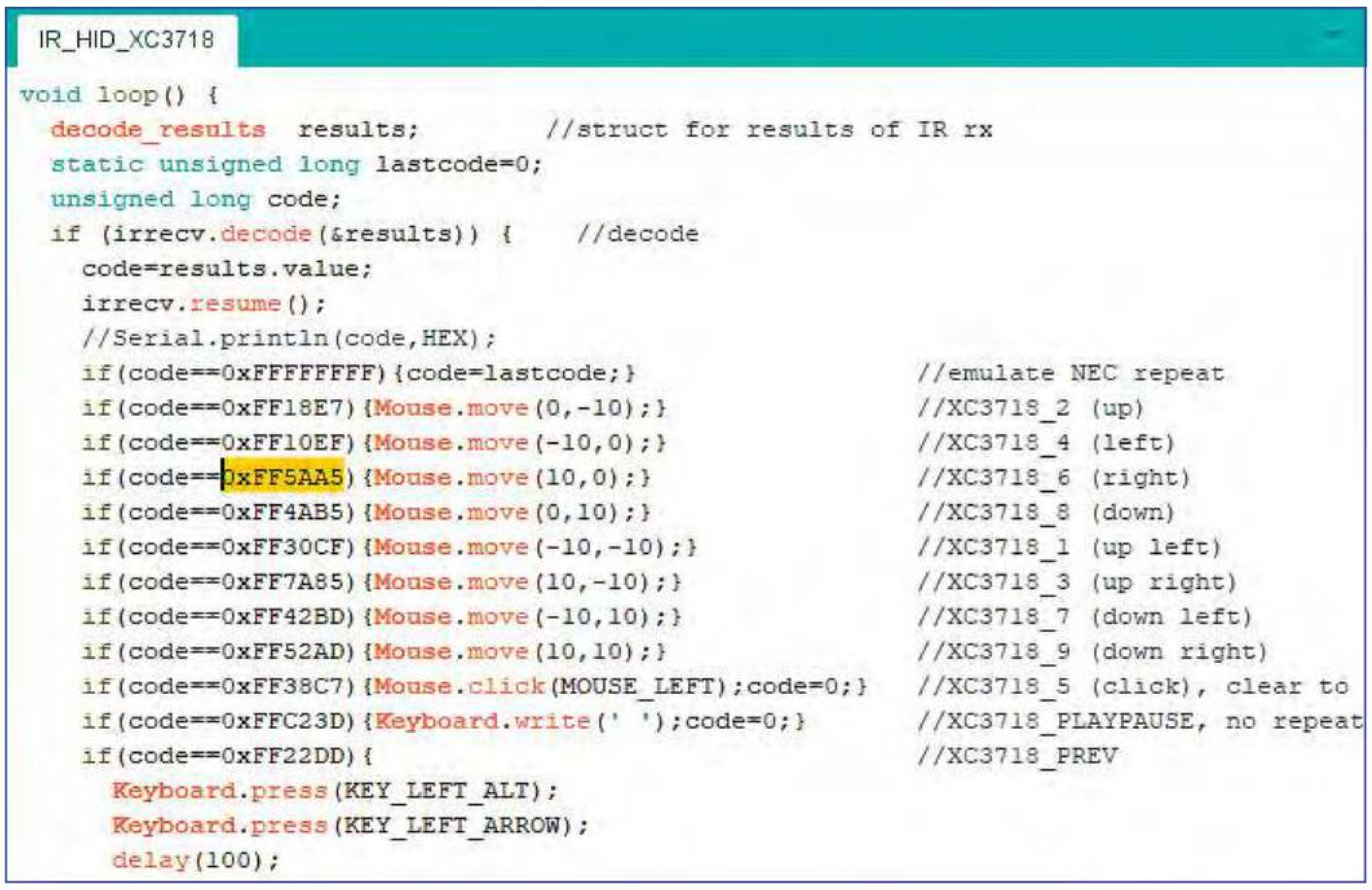
If you want to click a different button, do it like this:

```
Mouse.click(MOUSE_RIGHT);
```

Note that all mouse movements are relative. You can't send a command to move the pointer to a particular position on the screen. If you have to do this, you might be able to come up with a scheme where you move the mouse into one corner of the screen and then move it relative to that point, but we won't go into details as we haven't tried it.

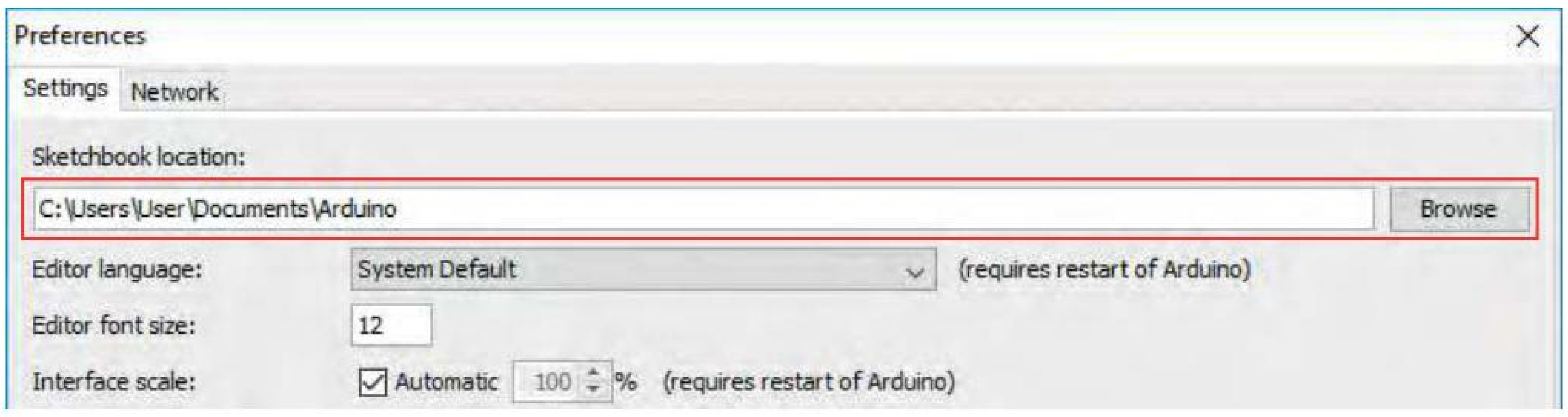
In practice, the best way to implement mouse cursor control with an IR remote is to have a button each for up, down, left, right and click. Extra buttons, if available, can be used for diagonal movements.

This makes steering the pointer feel a bit like playing an old video game with a joystick, but it is fine for some basic screen navigation; eg, to select a video to play.



```
void loop() {
  decode_results  results;        //struct for results of IR rx
  static unsigned long lastcode=0;
  unsigned long code;
  if (irrecv.decode(&results)) {    //decode
    code=results.value;
    irrecv.resume();
    //Serial.println(code,HEX);
    if(code==0xFFFFFFFF){code=lastcode;}                     //emulate NEC repeat
    if(code==0xFF18E7){Mouse.move(0,-10);}                   //XC3718_2 (up)
    if(code==0xFF10EF){Mouse.move(-10,0);}                   //XC3718_4 (left)
    if(code==0xFF5AA5){Mouse.move(10,0);}                    //XC3718_6 (right)
    if(code==0xFF4AB5){Mouse.move(0,10);}                    //XC3718_8 (down)
    if(code==0xFF30CF){Mouse.move(-10,-10);}                 //XC3718_1 (up left)
    if(code==0xFF7A85){Mouse.move(10,-10);}                  //XC3718_3 (up right)
    if(code==0xFF42BD){Mouse.move(-10,10);}                  //XC3718_7 (down left)
    if(code==0xFF52AD){Mouse.move(10,10);}                   //XC3718_9 (down right)
    if(code==0xFF38C7){Mouse.click(MOUSE_LEFT);code=0;}      //XC3718_5 (click), clear to
    if(code==0xFFC23D){Keyboard.write(' ');code=0;}          //XC3718_PLAYPAUSE, no repeat
    if(code==0xFF22DD){                                      //XC3718_PREV
      Keyboard.press(KEY_LEFT_ALT);
      Keyboard.press(KEY_LEFT_ARROW);
      delay(100);
```

By changing the value highlighted, we can change which IR code/button press the Leonardo responds to. For this line of the sketch, if the current code matches, a signal is sent to the PC to move the mouse pointer 10 pixels to the right.



Sketchbook location: C:\Users\User\Documents\Arduino

Editor language: System Default (requires restart of Arduino)

Editor font size: 12

Interface scale: ☑ Automatic 100 % (requires restart of Arduino)

To manually install the libraries (rather than using the library manager), unzip or copy them into the Arduino libraries folder. This can be found by going to the File → Preferences menu in the Arduino IDE and looking for the 'Sketchbook location', as shown above. The libraries are stored in a subfolder at this location.

Getting the infrared codes

If you are using the suggested Jaycar remote control and already have the Arduino IDE installed, jump ahead to 'Uploading the main sketch'.

If you have an existing remote control you would like to make work, you will first need to upload the **IR_Code_Typer** sketch to find out which codes correspond to which keys. (Available for download from the *PE* website.)

To compile and upload the software that runs on the board, we need to have the Arduino IDE (Integrated Development Environment) installed – available from: **www.arduino.cc/en/main/software** for Windows, macOS and Linux. Download and install a version to suit your operating system and start the Arduino IDE. You will need at least version 1.6.4 to use the Library Manager in the next step.

Open the Library Manager by going to the Sketch → Include Library → Manage Libraries menu and search for 'irremote'. When you find it, click on the install option that is presented.

If the Library Manager is not working or not available, you have the option of installing the **IRremote.zip** library supplied in the download package using the 'Add .ZIP Library' option in that same menu.

Now plug the device into a USB port on the computer and select the board's serial port in the Tools → Port menu. Observe whether the board is seen as a 'Leonardo' or 'Micro', and based on this, select either 'Arduino Leonardo' or 'Arduino/Genuino Micro' under the Boards menu. If you choose the wrong option it simply won't work; so if in doubt try one or the other.

Before uploading the code, open a text editor such as Notepad or Leafpad, because the board becomes a keyboard device immediately after the upload completes.

Now open the **IR_Code_Typer.ino** sketch file, which you will have extracted from the download package, then click 'Upload' (or press CTRL+U on your keyboard).

Assuming the upload completes successfully, switch to the text editor that you opened earlier, then point your IR remote control at the unit and press one of the buttons.

You should see a hexadecimal value appear and pressing a different button should give you a different code. You may also get different codes if you hold the button down.

A good way to record the codes is to open a spreadsheet program and create a list with the button names that you want to use in the first column. Then move the cursor to the top of the second column and press each remote control button in turn, corresponding to the names in the spreadsheet's first column.

The code should appear in that cell and the cursor will move to the next cell below.

Uploading the main sketch

You might like to try uploading the sketch to the board without making any changes, just to check that everything works as it should.

The sketch code we have created will work with the Jaycar XC3718 remote control pictured earlier, but it can be supplemented with your own codes.

By default, it uses the numbers 1-9 as a joystick type interface, with the 5 key being the same as a left mouse click and the other numbers moving the pointer in different directions by 10 pixels at a time.

For example, number 4 is to the left of centre so it will move the mouse to the left.

We've also set up the Play/Pause button to emulate a spacebar press, and the Previous and Next buttons

Parts List

1 infrared remote control (eg, Jaycar XC3718)
1 infrared receiver module (eg, Jaycar ZD1952, Altronics Z1611A)

Beetle-based version

1 DFRobot Beetle or equivalent (eg, ProMicro)

Leonardo-based version

Arduino Leonardo board or equivalent (eg, Jaycar XC4430, Altronics Z6214)
1 set of plug-socket breadboard leads (eg, Jaycar WC6028, Altronics P1017)

generate Alt-Left and Alt-Right keypresses respectively. These last two correspond to forward and back on many web browsers too.

If you are using a different remote control or want to change what the buttons do, you will need to modify the code. Specifically, you will be modifying the series of `if` statements which check to see which IR code has been received and then perform an appropriate action.

Before making any modifications, save the Sketch file under a different name so that you don't overwrite and lose the original.

Using your spreadsheet as a reference, replace the hexadecimal value in each `if` statement with one of the button codes that you noted earlier. Then, inside the braces that follow that `if` statement, you will need to change or add the code to send the necessary keyboard or mouse events to the computer.

For example, let's say that in response to button code `0xFF1234` being received, you want to generate a keypress equivalent to pressing CTRL+ALT+t on the keyboard. Your new `if` statement would look like:

```
if (code == 0xFF1234) {
  Keyboard.press(KEY_LEFT_CTRL);
  Keyboard.press(KEY_LEFT_ALT);
  Keyboard.press('t');
  delay(100);
  Keyboard.releaseAll();
  code=0;
}
```

The `code=0;` line towards the end should be included if you do not want the action to be repeated if the key is held down. If you do want it to repeat, leave that bit out.

Once you have done this with all the buttons you want to use on the remote and removed any extraneous `if` statements which may be left over from the original code, you can proceed to upload this sketch to the main board. (You can handle codes from multiple remote controls in the same sketch.)

Having uploaded the sketch, check that it works as expected. If you find any keys are not responding or not doing what you think they should, check the code in the `if` statements.

Finalising the code

You might notice in the codes that we check for `0xFFFFFFFF`. This is a code emitted by remote controls that use the NEC encoding which indicates that the current key is being held down and the effect of that key should be repeated.

We implement this by saving the code of whatever key was last pressed and then substituting that code if a repeat code is seen.

What next?

It's a very useful device as described, but these Arduino boards have a number of spare pins and you could use these for other tasks that can also be controlled by the remote control.

For example, you could wire up some LEDs and arrange for remote buttons to switch them on and off for some instant mood lighting.

You could even consider integrating some code to switch remote power points on and off. You could do this using some Arduino code provided by Jaycar that works with the wireless power point switches. This can be downloaded from: **www.jaycar.com.au/iot-wireless-switch**

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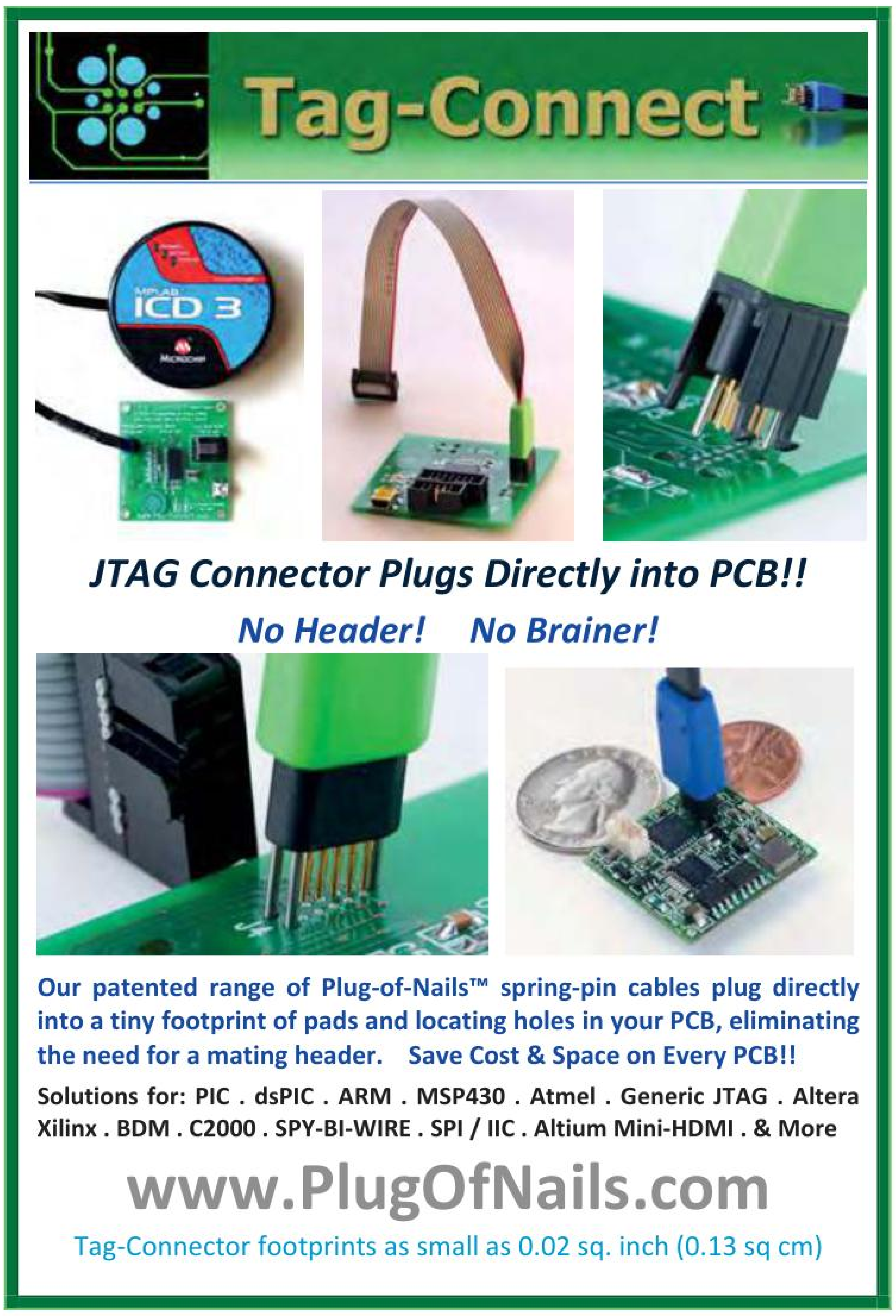

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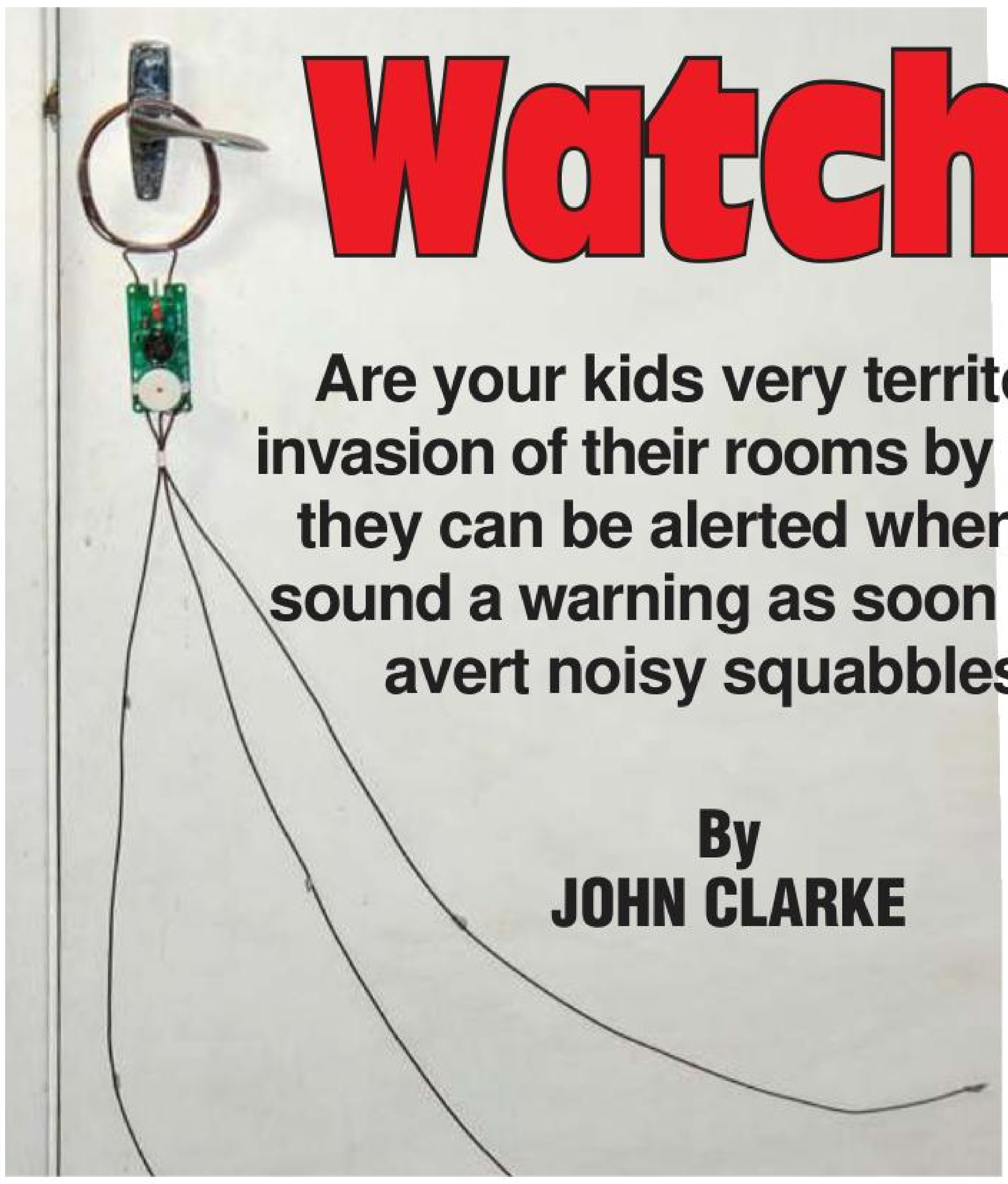
Watchdog Alarm

Are your kids very territorial? Do they want extra security against invasion of their rooms by pesky siblings? Why not build an alarm so they can be alerted when their room is about to be invaded? It will sound a warning as soon as the door knob is touched and possibly avert noisy squabbles. The kids will love it... but of course, you may have to make each of them one!

By
JOHN CLARKE



Features

- **Detects the presence of a hand on a doorknob**
- **Option of piezo transducer or louder siren for alarm**
- **Testing period during initial power on without sounding alarm**
- **LED shows initial test period, normal monitoring and alarm**

A kid's domain is sacrosanct – especially if they are fortunate enough to have their own room. But no amount of threats or retribution will keep a sibling (or parent!) out when they're uninvited! Kids are sneaky that way. . .

This *Watchdog Alarm* is effective and certainly preferable to more drastic measures such as trip wires, buckets precariously balanced above doorways, trapdoors, Gatling guns and other schemes which war-like adolescent humans are likely to dream up to protect their room, cave or lair.

Having an audible warning means the hostile room occupant will immediately be alerted to an undesirable alien (eg, little brother) touching the doorknob, even before they open the door.

That warning may or may not be sufficient to prevent the mischief maker from creating mayhem by opening the door, knowing they have been detected, but it will certainly be a deterrent against further incursions.

(OK, we're not seriously suggesting this alarm as a proper security device... but it could have other applications where a change in the capacitance of a metal object needs to be detected.)

The idea for this project came from an article in the April 1981 edition of *Electronics Australia* for a portable burglar alarm. Powered from a 9V battery, it used a hex Schmitt trigger connected as a couple of oscillators and a timing circuit to drive a siren whenever the doorknob was touched.

So, with child territoriality in mind, we have updated this concept using a low power microcontroller. The resulting *Watchdog Alarm* uses an 8-pin micro on a small PCB which can be easily assembled and set up within an hour. It is powered from a small, onboard 3V cell and is presented as a bare printed circuit board (PCB) assembly to minimise cost.

A sensor loop is placed over the doorknob (no electrical connection required) to detect when this is touched. The *Watchdog Alarm* is turned on and off with a toggle switch and an indicator LED flashes to show that the doorknob is being monitored.

When the *Watchdog Alarm* is first switched on, the indicator LED flashes rapidly for about 10s, during which time the doorknob can be touched without sounding the alarm. Touching the doorknob during this period will cause the LED to light fully. You can use the 10s period to check the operation of the *Watchdog Alarm*. We'll explain this later in the setup section.

Once the 10s period has expired, the LED will flash about once per second to indicate that the *Watchdog Alarm* is armed. Touching the doorknob now will cause the alarm to sound.

There are two alarm options. One is an on-board piezo transducer that beeps twice every three seconds (about 1.5Hz) if the alarm is triggered.

For a much louder alarm you can use an off-board piezo siren. This is better at waking more comatose room occupants (no guarantees, though).

Block and circuit diagrams

Fig.1 shows the block diagram. As already noted, this alarm uses a microcontroller and it produces a 2MHz signal which is applied to the doorknob which is monitored at the same time.

If a pesky human touches the doorknob, the person's body capacitance will effectively shunt away the 2MHz signal and this will cause the micro to sound the alarm. The circuit requires a 'counterpoise', made from three lengths of wire and this serves to provide a virtual ground reference.

The circuit, shown in Fig.2, is based on a PIC12F617 8-pin microcontroller (IC1).

Switch S1 connects the 3V button cell and diode D1 provides reverse polarity protection. If the cell is somehow inserted incorrectly, the diode will conduct and safely limit the reverse voltage to IC1 at around –0.6V. Admittedly, the cell holder we use makes it rather difficult (if not impossible!) to allow the cell to be inserted incorrectly, so that is an added protection.

IC1 uses an internal 8MHz oscillator, which is divided by four to provide a clock signal of 2MHz at pin 3, CLKOUT.

Most of the time, IC1 is in sleep mode and its internal 8MHz oscillator is stopped. It is woken once a second by its internal watchdog timer (yep, that's where we got the name from!) to flash the red indicator LED and check if the doorknob is being touched. Sleep mode reduces the current consumption of IC1 down to a very low level in order to maximise the life of the cell.

In more detail, the internal watchdog timer runs continuously and once a second it wakes up IC1. The 8MHz oscillator then starts, the program in IC1 runs and the CLKOUT output at pin 3 then produces the 2MHz signal. This signal is applied via an

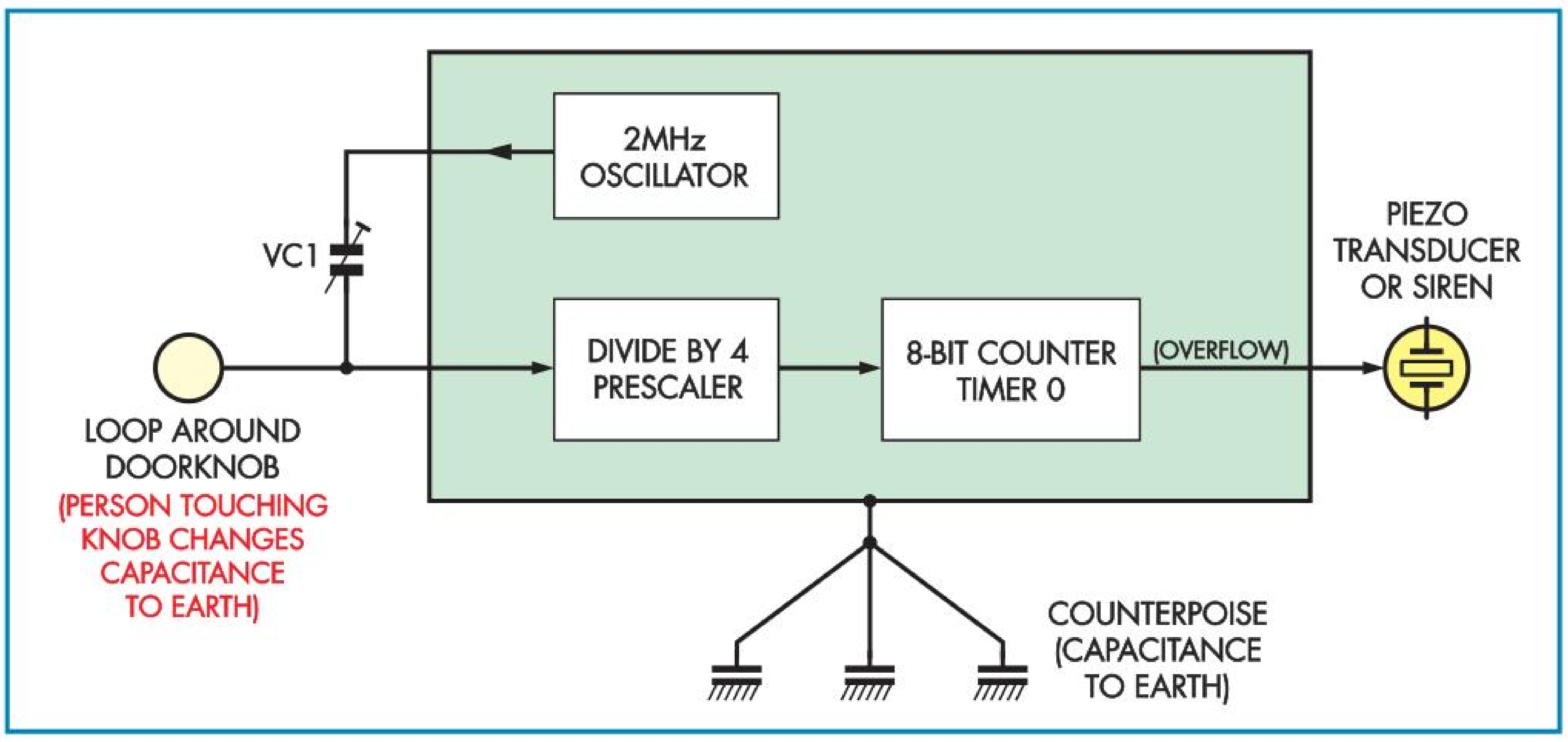

2MHz
OSCILLATOR
VC1
DIVIDE BY 4
PRESCALER
8-BIT COUNTER
TIMER 0
(OVERFLOW)
PIEZO
TRANSDUCER
OR SIREN
LOOP AROUND
DOORKNOB
(PERSON TOUCHING
KNOB CHANGES
CAPACITANCE
TO EARTH)
COUNTERPOISE
(CAPACITANCE
TO EARTH)

Fig.1: the *Watchdog Alarm's* microcontroller feeds a 2MHz signal via trimmer capacitor VC1 to the doorknob sensor loop. If someone touches the doorknob, their body capacitance shunts this signal to ground. The micro senses this and sounds the piezo alarm or siren.

adjustable trimmer capacitor (VC1) to the T0CKI (pin 5) via 470Ω resistors. The wire loop for the doorknob sensing is attached to the trimmer capacitor at the opposite side to CLKOUT.

If the doorknob is not touched, the input to IC1 at T0CKI will receive the 2MHz signal passing through the trimmer capacitor.

The block diagram of Fig.1 depicts what happens inside IC1. The 2MHz signal is applied to a divide-by-four prescaler and then to an 8-bit counter (TIMER0). At 2MHz, the output from the prescaler is 500kHz (2MHz/4). TIMER0 counts at the 500kHz rate and the overflow output (T0IF) goes high after 256 counts – the full count of the 8-bit counter.

TIMER 0 reaches the full count in 512µs. If its output does not go high after this period, then the software assumes there is no signal. Lack of signal would mean that the 2MHz signal is being diverted to ground by flow through the doorknob by body capacitance.

Several extra parts are used between the VC1 output and the T0CKI input. This includes the 470Ω resistors and diodes D2 and D3 which are included to protect the pin 5 input. Should the person have a static charge before touching the doorknob, diodes D2 or D3 will clamp the voltage to the positive or 0V supply depending on the static voltage polarity. The 470Ω resistor to D2 and D3 limits current. The next 470Ω resistor to pin 5 protects the internal protection diodes of IC1.

The 1MΩ resistor is there to pull pin 5 to 0V so the input does not float at a voltage between 0V and the supply. Additionally, during sleep, the pin 5 input is changed from an input to a low output, further ensuring the input is not floating. A floating input will cause IC1 to draw extra current.

Piezo drive

The GP3 input (pin 4) connects to the 3-pin header JP1. The position of a 2-pin jumper on this header selects whether you use the lower-cost on-board piezo transducer or the louder off-board piezo siren. The selector is necessary because each is driven differently. The piezo transducer is driven by a burst signal generated by the micro, while the piezo siren has its own internal constant-tone generator and is turned on when pin 7 goes high, feeding it with 3V DC.

When set in the piezo position, GP3 is tied low and if the doorknob is touched to trigger the alarm, the piezo transducer sounds, as pins 6 and 7 (GP1 and GP0) alternately go high and low, to deliver bursts of 4kHz signal. In a small room and at close quarters, this can be quite loud.

Certainly, there is no mistaking that the miscreant has been 'pinged'. The alarm will sound whenever the doorknob is touched. As soon as the doorknob is released, the alarm will stop.

The scope screen grabs of Fig. 3 and 4 show the complementary drive signals applied to the piezo transducer from pins 6 and 7. In Fig.4, the two signals are at 4.05kHz and have an amplitude very close to 2.06V and 2.44V peak-to-peak, not allowing for the overshoot spikes. Therefore, the total signal applied to the transducer will be close to the sum of those voltages: 4.5V peak-to-peak, as shown in the purple mathematical trace of Fig.3.

By the way, the reason the signals on both sides of the transducer are not identical is explained by the presence of the series 100Ω current-limiting

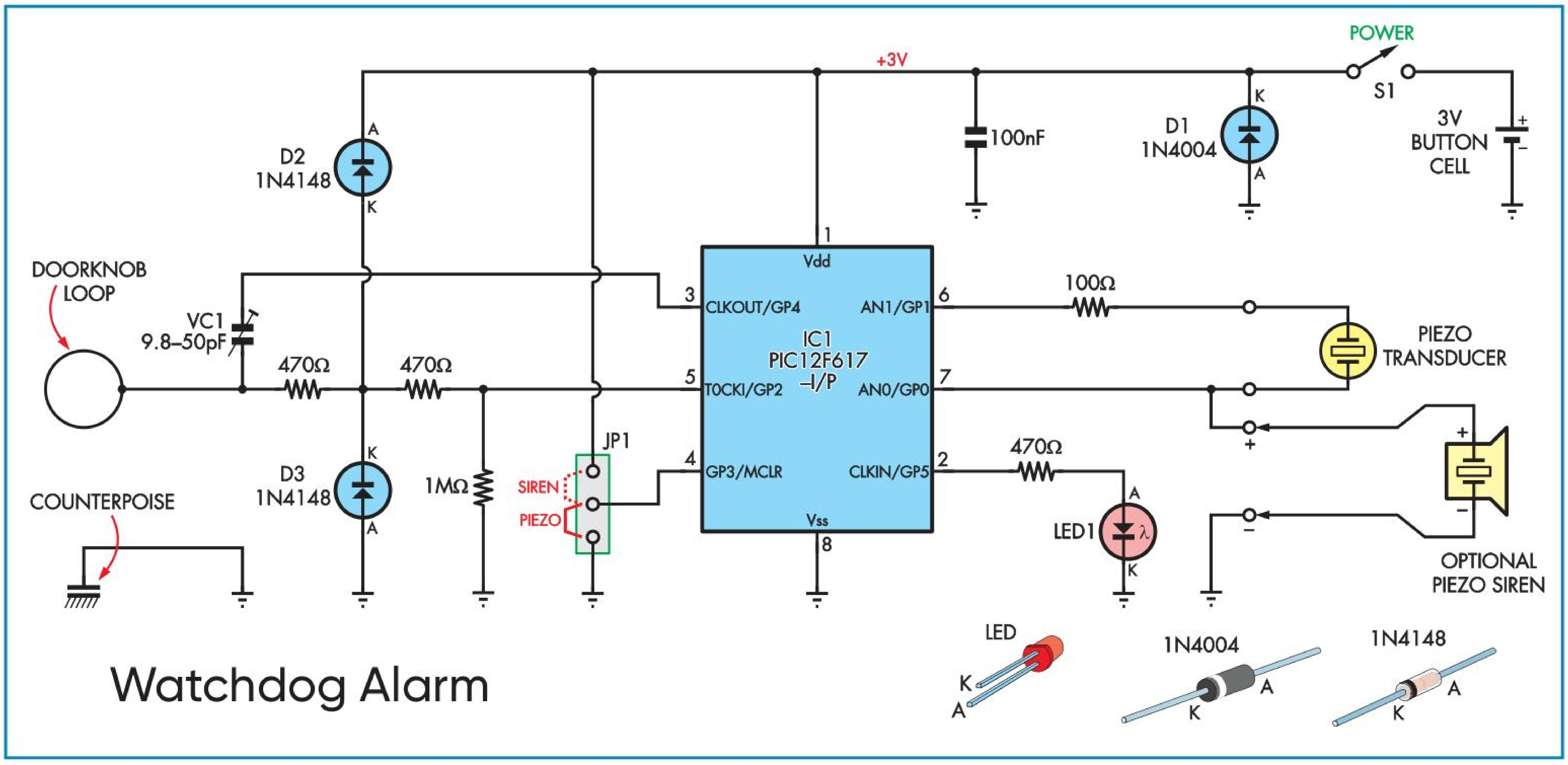
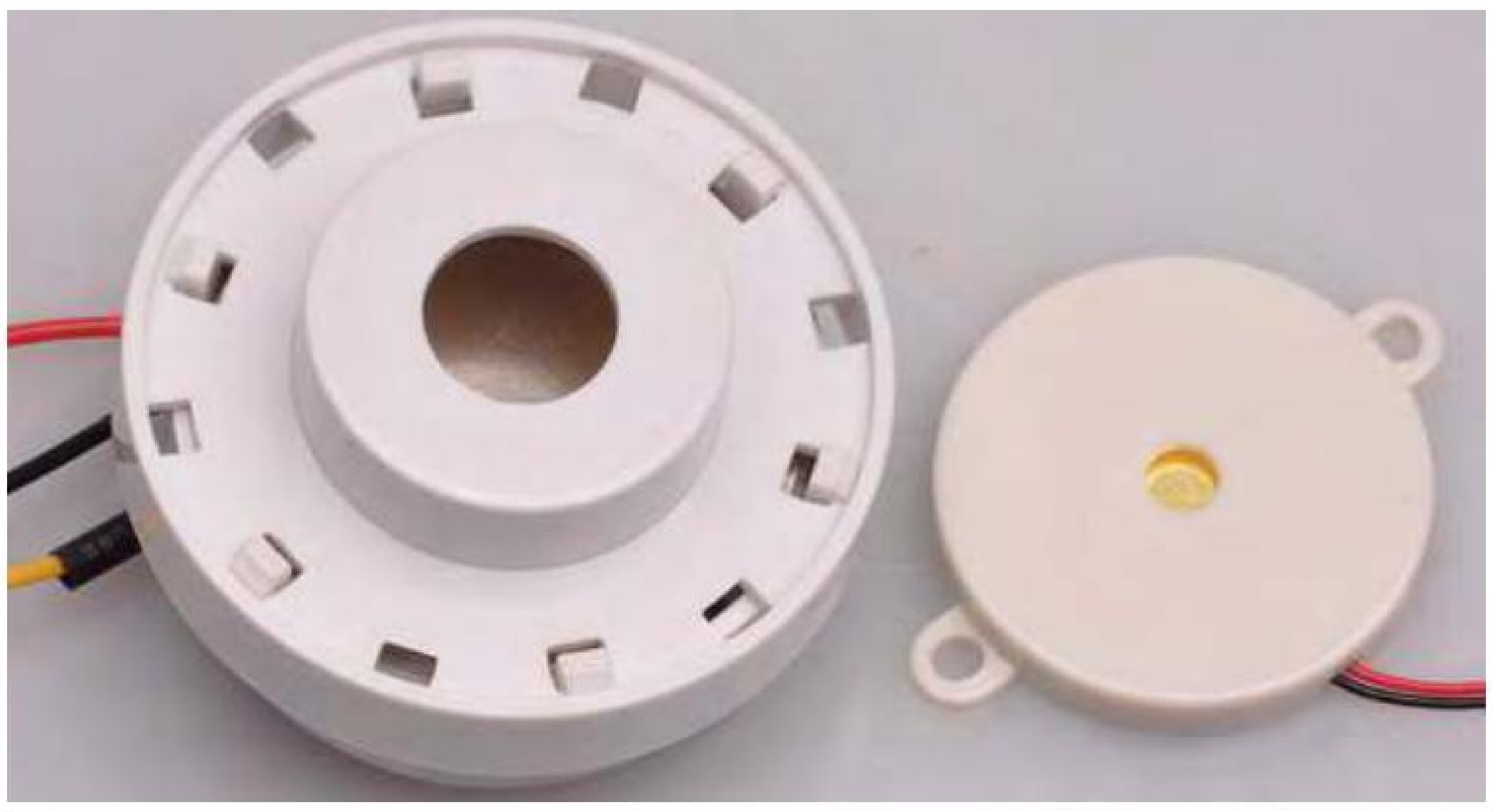

POWER
+3V
S1
3V
BUTTON
CELL
100nF
D1
1N4004
K
A
D2
1N4148
A
K
DOORKNOB
LOOP
VC1
9.8–50pF
470Ω
470Ω
1
Vdd
3
CLKOUT/GP4
AN1/GP1
6
100Ω
IC1
PIC12F617
–I/P
5
T0CKI/GP2
AN0/GP0
7
PIEZO
TRANSDUCER
+
–
JP1
4
GP3/MCLR
CLKIN/GP5
2
470Ω
D3
1N4148
1MΩ
SIREN
PIEZO
COUNTERPOISE
Vss
8
LED1
A
K
λ
OPTIONAL
PIEZO SIREN
LED
K
A
1N4004
1N4148
Watchdog Alarm

Fig.2: the micro provides two alarm options. The first is a piezo transducer driven with anti-phase tone burst signals which effectively doubles the single pin output voltage. The second is a lounder off-board piezo siren which has its own internal oscillator. LED1 shows the alarm status.



The two 'siren' options: shown here not far off life size. On the left is the louder of the two which must be mounted off the PCB. At right, the piezo transducer, which can be mounted directly on the PCB.

resistor from pin 6. Note that we are running the piezo transducer at close to its resonant frequency to maximise its audible effect.

Fig.4 shows the same complementary drive signals but at a slower sweep speed of 5ms/div. This shows how the signal bursts are rapidly chopped, which gives it a burbling sound that is more attention-getting.

Finally, Fig.5 shows the same signal at the very low sweep speed of 500ms/div and this shows the 260ms duration and 1.55Hz frequency of burbled tone bursts from the transducer.

When the JP1 jumper is in the siren position, the siren is powered by a high level (ie, the V_{CC} supply voltage) at the GP0 output with its other terminal connected permanently to ground.

Construction

The *Watchdog Alarm* is constructed on a PCB, available from the *PE PCB Service*, coded 03107181. It measures 42 × 93mm and is presented as a bare PCB hung on the doorknob.

Fig.6 shows the PCB overlay. Begin construction by installing the resistors. There are only three values, but do use a multimeter to check the value of each before inserting into the PCB.

Diodes D1 to D3 can now be installed, taking care to orient correctly and noting that D1 is the 1N4004 and the remaining diodes are 1N4148s. The 100nF capacitor can be fitted next, followed by the IC socket (for IC1). It must be oriented with the notch facing the 100nF capacitor.

The 3-way pin header for JP1 is next. Optional PC stakes are installed at the wiring points for the piezo transducer or for the siren (the wires could instead be directly soldered to the relevant pads).

Make sure the plus terminal of the button cell holder is oriented toward IC1 on the PCB. LED1 is mounted raised off the PCB (we made ours about 10mm high but it can be mounted higher). Take care with orientation – the longer (anode) lead goes to the hole marked with the 'A'.

VC1 can be installed either way round on the PCB. Switch S1 is inserted into position and soldered in place. The switch applies power when the toggle is up. The toggle is protected inside the PCB cut out so is less likely to be inadvertently moved. Leave the siren or piezo transducer off for the moment.

Programming the microcontroller

A programmed PIC12F617-I/P microcontroller is available from the SILICON CHIP Online Shop. However, if you want to program the PIC yourself, the file 0310718A.hex can be downloaded from the *PE* website.

There is one DIY programing caveat: we are not using pin 4 of IC1 as the master clear ($\overline{\text{MCLR}}$) input but as an input for JP1. For master clear we use the internal $\overline{\text{MCLR}}$ instead. Some programmers will not support programming when the internal MCLR and internal oscillator are selected. If you are using a PICkit 3, the warning can be ignored and programming continued.

Make sure IC1 is oriented correctly before inserting into its socket (the notch on the IC matches the notch on the socket).

Now install the CR2032 cell in its holder and place a jumper link onto the 3-way header at JP1. Switch on S1 and if all is well, the LED will light or flash rapidly to acknowledge power has been connected.

All that's left now is to fit the piezo transducer or the off-board siren. If you choose the piezo transducer, it is mounted to the PCB on 9mm spacers using 15mm M3 screws. It sits up 10mm above the PCB surface as there are other components (including IC1) underneath. The two flanges on the transducer housing will need the holes drilled out to 3mm.

There's a little wrinkle here: the piezo housing flanges do not *quite* allow for M3 screw heads, as the heads foul the circular side of the transducer. With our prototype, the sides of the heads were filed down for each screw that secures the piezo transducer.

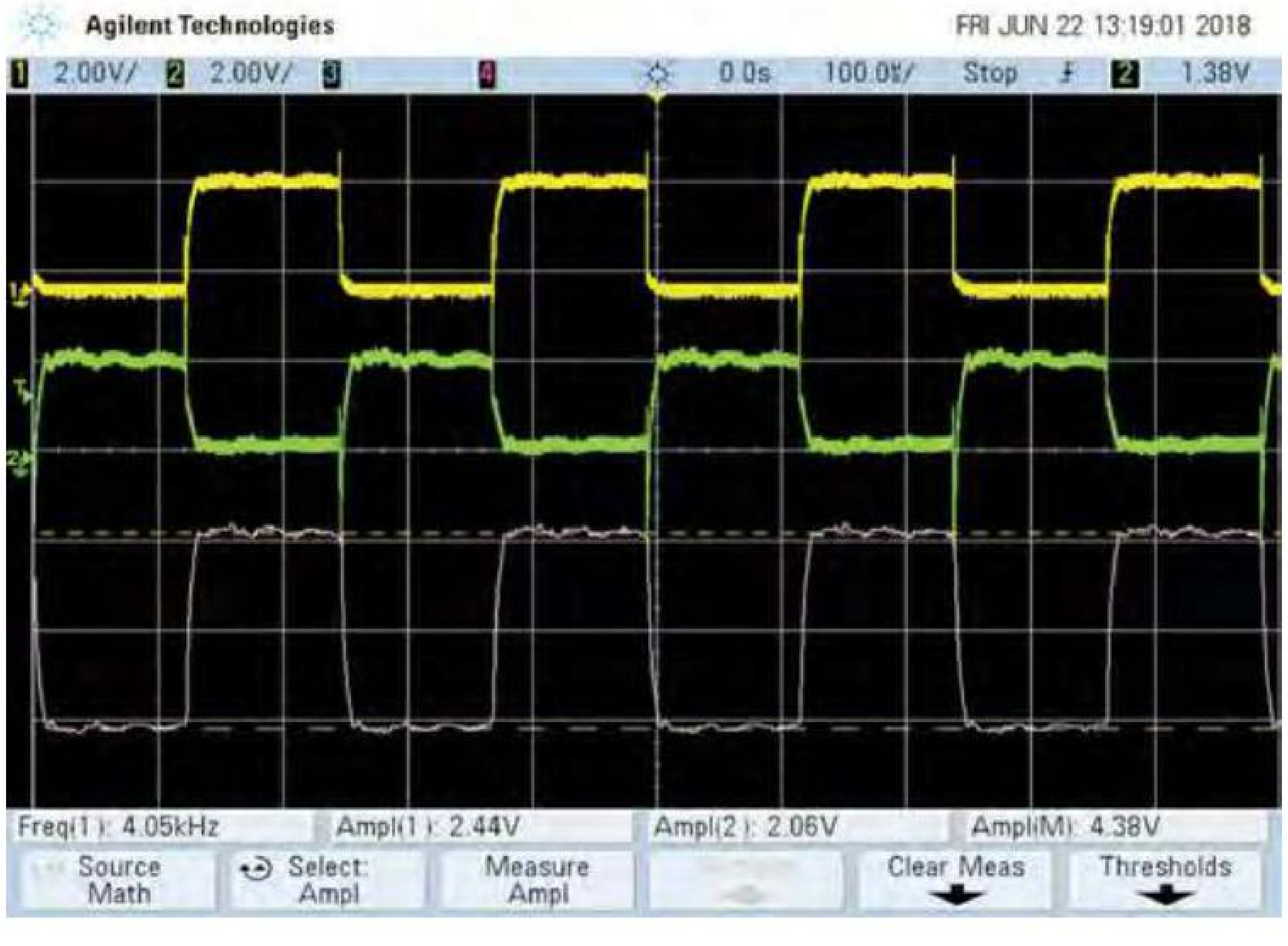


Fig.3: the complementary (anti-phase) drive signals applied to the piezo transducer from pins 6 and 7. The two signals are at 4.05kHz and have an amplitude very close to 2.06V and 2.44V peak-to-peak, not allowing for the overshoot spikes. Therefore, the total signal applied to the transducer will be close to the sum of those voltages 4.5V peak-to-peak, as shown in the purple mathematical trace.

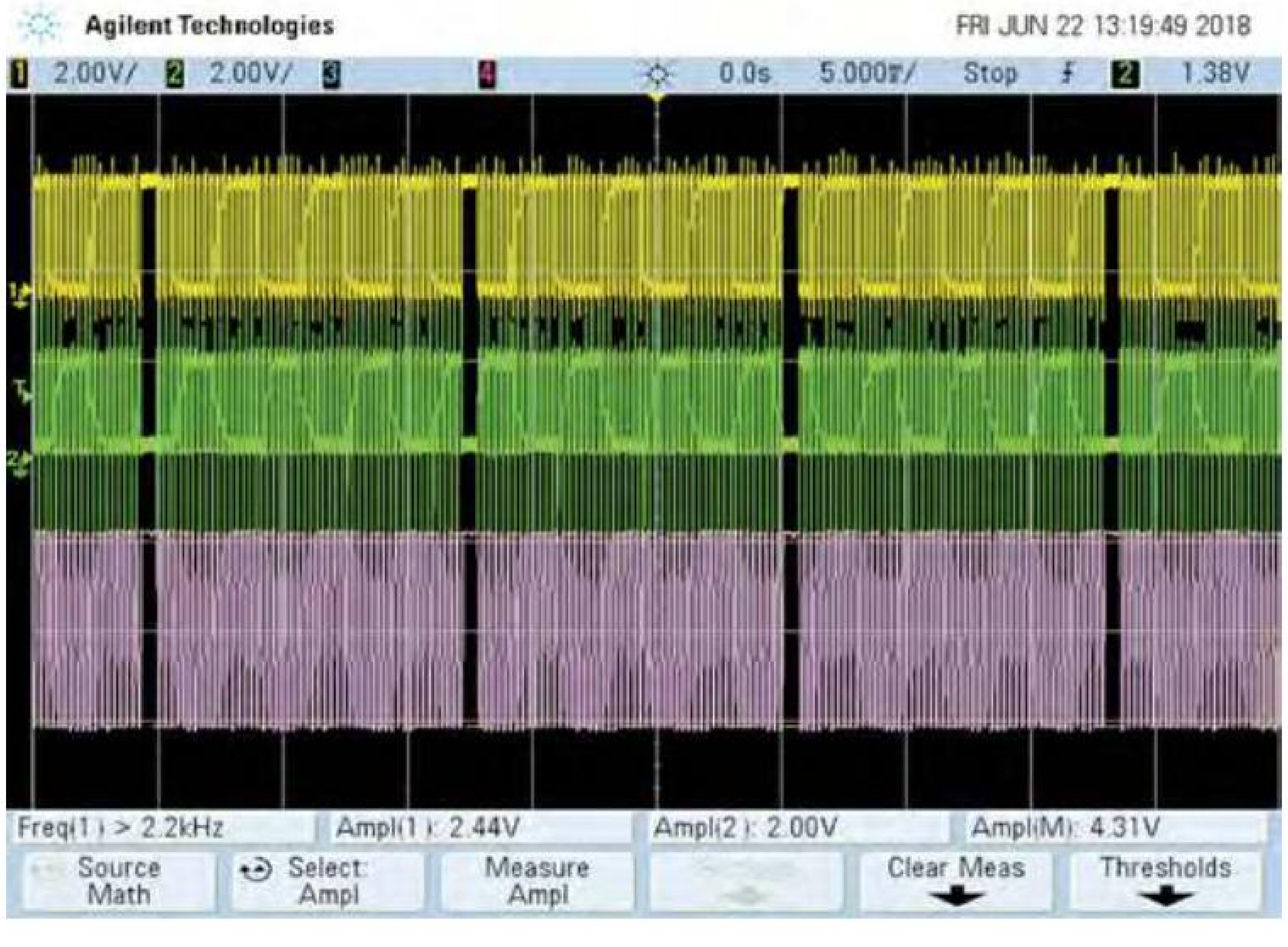


Fig.4 shows the same complementary drive signals fed to the transducer as in Fig. 3, but now at a slower sweep speed of 5ms/division. This shows how the signal bursts are rapidly chopped to give it a 'burbling sound', which is more attention-grabbing. Note that we are running the piezo transducer at close to its resonant frequency to maximise its audible effect.

Parts list – Watchdog Alarm

1 double-sided PCB, coded 03107181, 42 x 93mm
1 SPDT PCB toggle switch (S1) [Altronics S1421]
1 20mm PCB button cell holder [Jaycar PH-9238, Altronics S5056]
1 CR2032 lithium cell
1 8-pin DIL IC socket
1 piezo transducer [Jaycar AB-3440, Altronics S6140] ***OR***
11-13V pulsating piezo siren [Jaycar AB3456, Altronics S6117]
1 3-pin header with 2.54mm spacing (JP1)
1 jumper shunt (JP1)
2 PC stakes (optional)
2 M3 tapped x 9mm spacers
4 M3 x 6mm screws (at least two polycarbonate or nylon)
1 4m length of multistrand insulated wire (eg 24 x 0.2mm)
1 150mm length of 6mm-diameter heatshrink tubing
4 10mm diameter self-adhesive surface savers (stick-on feet)

Semiconductors
1 PIC12F617-I/P microcontroller programmed with 0310718A.hex (IC1)
1 1N4004 1A diode (D1)
2 1N4148 diodes (D2,D3)
1 3mm red high-brightness LED (LED1)

Capacitors
1 100nF 63V or 100V MKT polyester (Code 104 or 100n)
1 9.8-60pF trimmer capacitor (VC1)

Resistors (0.25W 1%)

1 1MΩ	3 470Ω	1 100Ω

Plastic polycarbonate or nylon screws are easier to file down than steel. To secure the two screws, the standoff is rotated onto the screw thread instead of rotating the screw.

Then the Piezo and standoffs can be secured to the PCB with the screws on the underside of the PCB.

If you choose the significantly louder off-board siren, then note that it is polarised – the negative (usually black) wire goes to the '–' siren terminal, while the 'pulse' wire (usually yellow) goes to the '+' siren terminal. The red wire is not used for three-wire sirens. By extending the siren's black and yellow wires with suitable hookup or thin figure-8 wire, you can locate it some distance away from the PCB – even a few metres or so, if you wish.

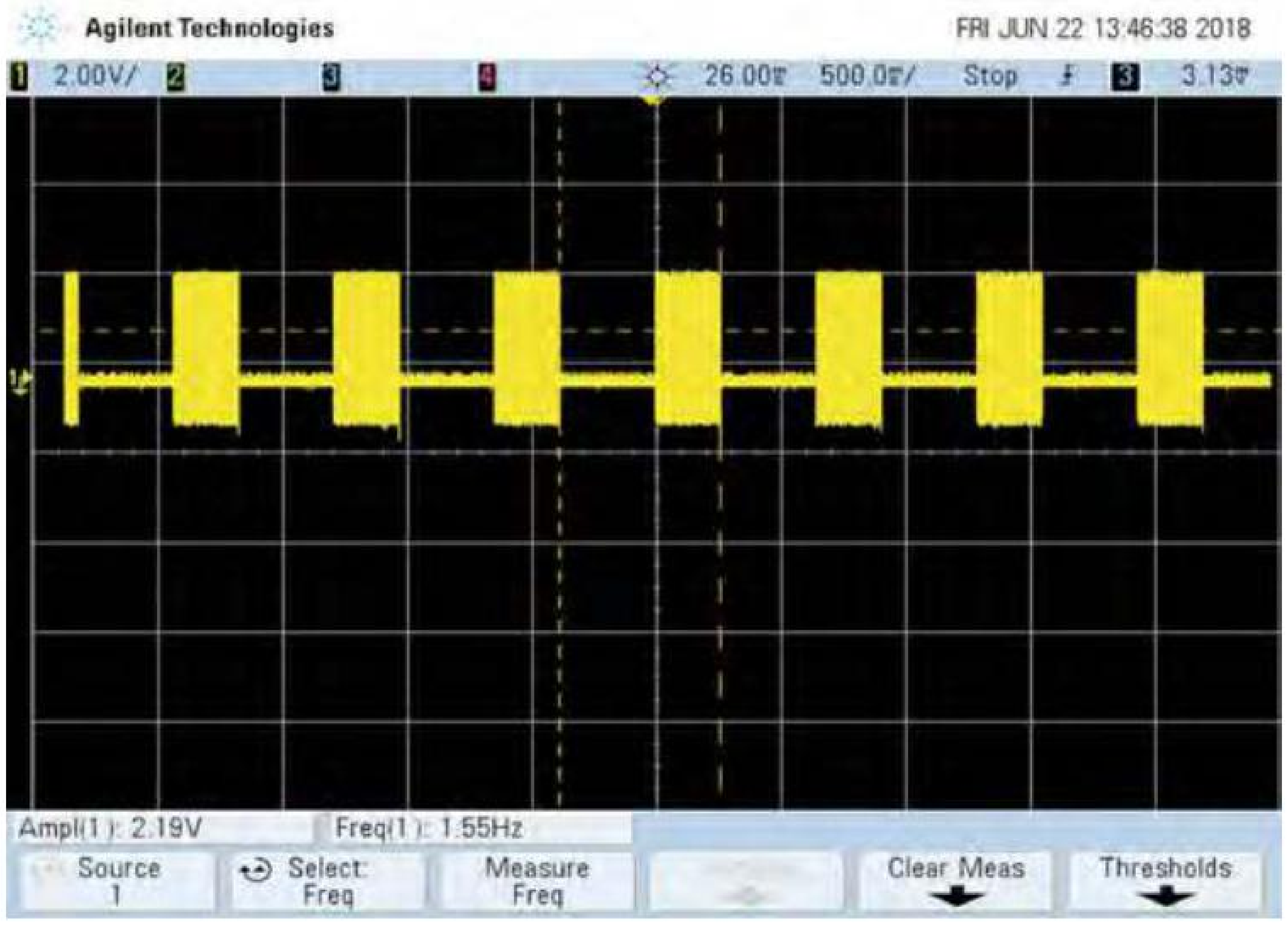


Fig.5: the piezo transducer signal from pin 7 of IC1,at the very low sweep speed of 500ms/div and this illustrates the 260ms duration and 1.55Hz frequency of the burbled tone bursts from the microcontroller. The burbling of the tone bursts makes the sound seem much louder.

Specifications

Supply voltage: 3V lithium cell which operates down to 2V

Current drain: 5.4μA at 2V; 7.5μA at 3V,with LED flashing 1Hz **(Piezo siren; when sounding add an extra 250μA)**

Expected cell life: ~1 year continuous use

Indicator flash: 3.2ms each 1.152s; constantly lit during detection

Testing period indication: LED flashes 3.5Hz during first 10s after power up. Fully lit during detection

Alarm response time: 0.5s (285ms during 10s testing period)

Piezo Transducer: 200ms bursts of 4.05kHz warbled at between 400Hz and 600Hz at a 1.55Hz rate

Piezo siren alarm: Uses intermittent siren or siren burst

Finally, don't forget to install the jumper shunt at JP1 in the correct position for the piezo transducer or siren, whichever is used (the PCB is clearly marked).

Wiring

The loops for the door handle are made up using a 1.2m length of insulated wire to make four turns at 90mm in diameter. We fed our loops through lengths of 6mm diameter heatshrink tubing so that the loops would stay in place without unravelling. Strip back the two wire ends a few millimetres and solder the ends into the doorknob holes on the PCB.

For the counterpoise, cut three 900mm lengths of insulated wire, strip insulation from one end of each and solder to the counterpoise holes located at the bottom of the PCB. In use, these are spread out over the door and fixed using Blu-Tack or tape.

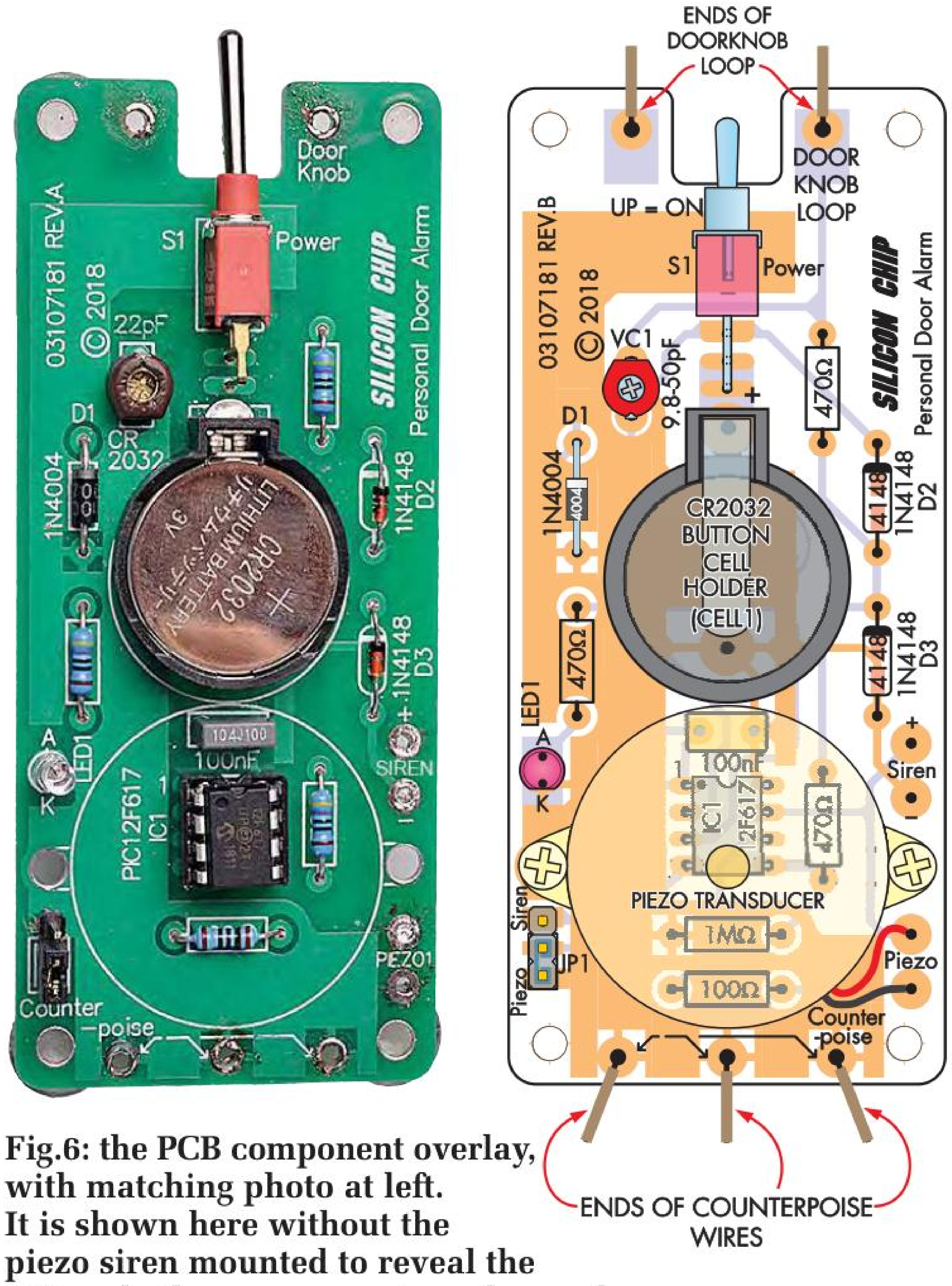


Fig.6: the PCB component overlay, with matching photo at left. It is shown here without the piezo siren mounted to reveal the PIC and other components underneath.

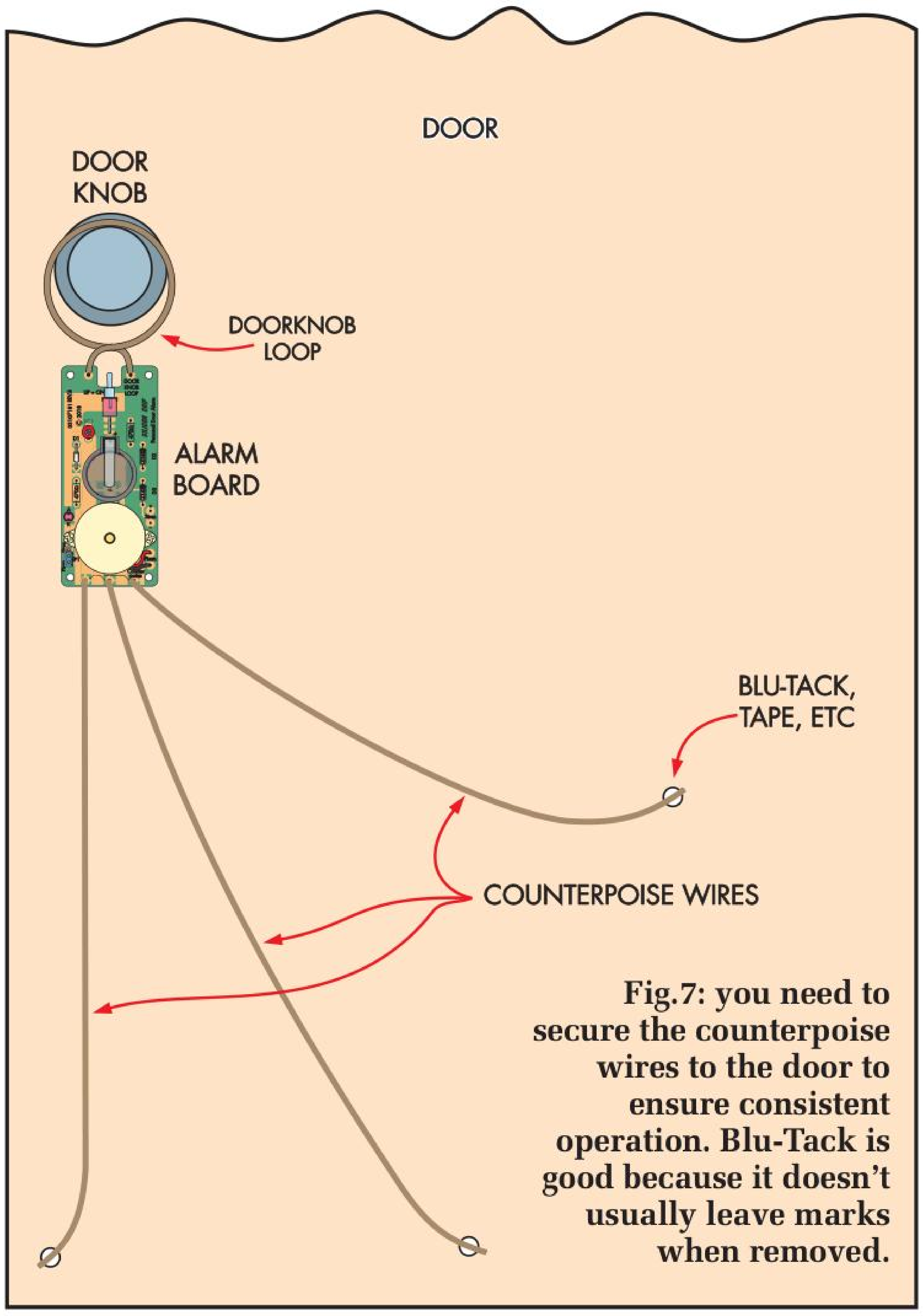


Fig.7: you need to secure the counterpoise wires to the door to ensure consistent operation. Blu-Tack is good because it doesn't usually leave marks when removed.

It makes sense, if possible, to use wires the same colour (or close) as the door to make them unobtrusive.

If you are placing this on a door that is not your own, then check that the mounting method does not stain or leave a mark on the door. In some cases, just having the three wires loosely dangling straight down will be sufficient.

Testing

Note that the *Watchdog Alarm* will not work if the door is metal-sheathed or if the door jamb is metal. It works best with timber-framed and timber doors with metal doorknobs. There is no need for an electrical connection from the doorknob to the wire loop, so the doorknob can be lacquered (such as coated gold or brass finishes) or exposed metal (such as brushed aluminium).

Place the wire loop over a doorknob and switch on. Adjust VC1 so that the LED flashes with the door handle untouched but lights up when touched. This is a trial and error adjustment, so try various settings of VC1. Once you find a good position where the hand is detected readily, the adjustment should not need changing again.

Note that for the first 10s after power is switched on, the LED will flash at a fast rate before flashing about once per second. That is if it is not detecting a touched door knob and the adjustment of VC1 is correct.

The period when the LED is flashing at the faster rate indicates that the piezo or siren, when connected, will not sound when the doorknob is touched until the 10 seconds has expired. This is to allow the testing of the *Watchdog Alarm* when first switched on without causing a lot of noise from the alarm.

If you wish, stick some self-adhesive surface savers (hemispherical adhesive buttons) to the corners of the PCB to protect against scratching the door.

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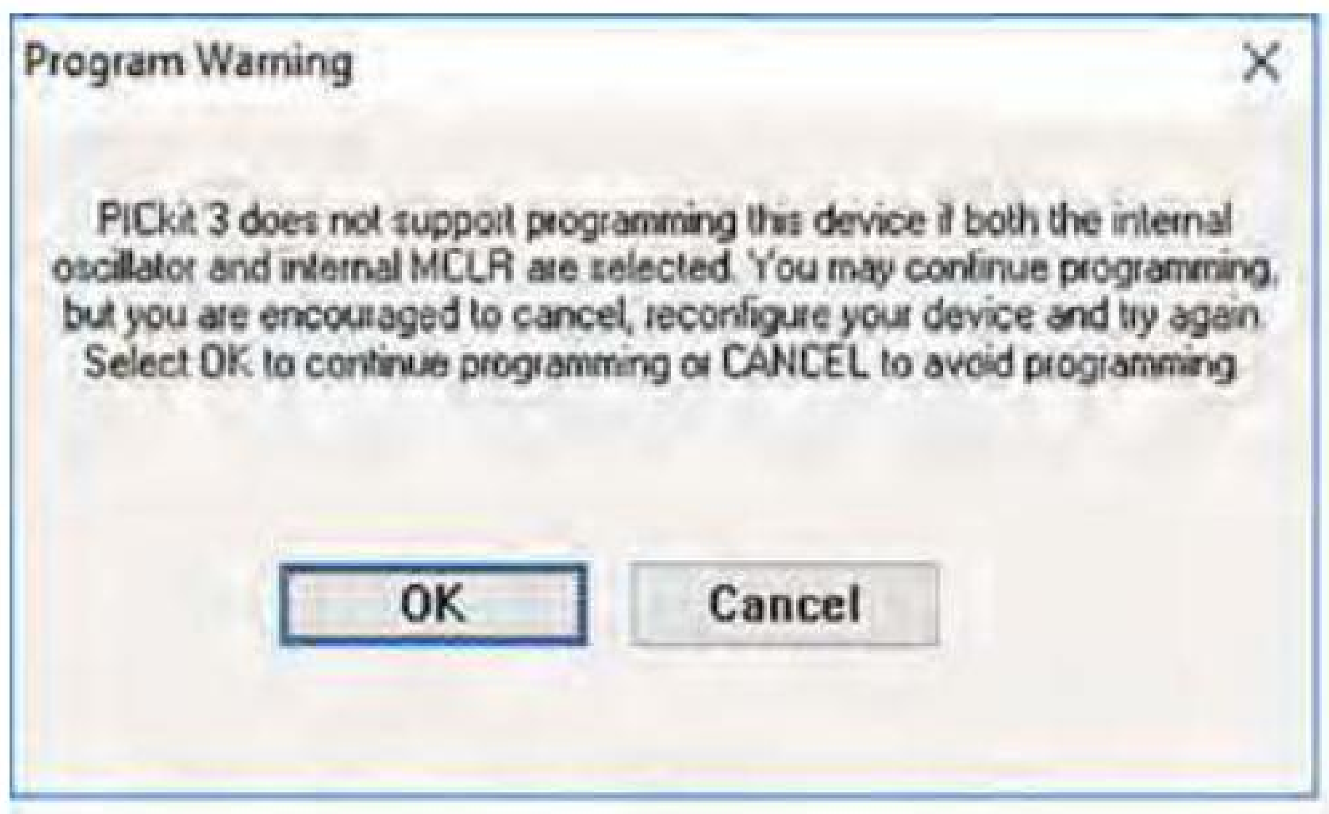
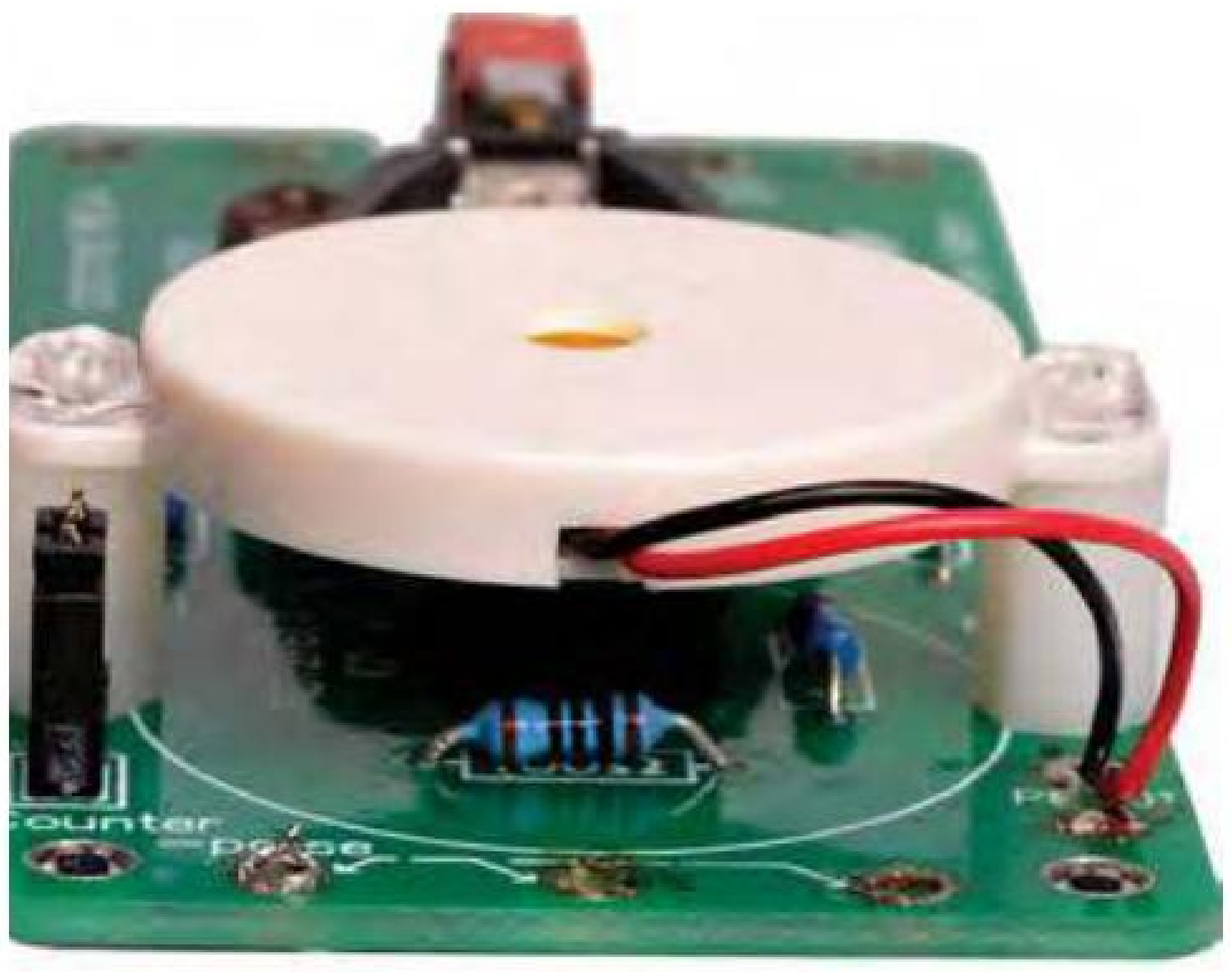

Program Warning

PICkit 3 does not support programming this device if both the internal oscillator and internal MCLR are selected. You may continue programming, but you are encouraged to cancel, reconfigure your device and try again. Select OK to continue programming or CANCEL to avoid programming

You're likely to see this warning when programming the PIC12F617-I/P. On the PICkit 3 it can be safely ignored, but other programmers may not support this programming.

Here's the door handle loop before heatshrinking and soldering in place. It consists of four turns of hookup wire, 90mm in diameter. The heatshrink helps hold its shape.



Here's how the on-board piezo transducer mounts on stand-offs above the PIC. The larger, more powerful siren can be mounted some distance away. It connects to the 'siren' pads, not the 'piezo' pads as seen here.

The lip on the piezo transducer doesn't quite allow the screw heads to fit, so we filed off one edge before mounting. We used nylon screws because they're a lot easier to file than metal screws.

And here it is shrunk and soldered. The loop simply drops over the door handle – no electrical connection is required because it detects capacitance – in this case, the capacitance of the person touching the doorknob on the other side of the door. . . GOTCHA!

Counter
-poise

The three counterpoise wires can, like the doorknob loop, be made from any surplus hookup wire. They should be about 900mm long each – but can be a little shorter if your door handle is lower than standard. They solder to the PCB but don't connect to anything else. The short length of heatshrink tubing provides strain relief to the solder joints on the PCB.

Electronics for a car dynamometer

by Julian Edgar

A dynamometer is the ultimate car analysis tool, but their cost makes them way out of reach for most amateur enthusiasts. Julian Edgar explains how, with a bit of electronics ingenuity, he got a second-hand ‘rolling road’ up and running for a fraction of the cost of a new one.

I’ve wanted a car dynamometer (often called a ‘rolling road’ in the UK) for many years – decades in fact. These are machines that are equipped with rollers and a braking mechanism. By placing the car on the ‘dyno’ rollers and then ‘driving’ through the engine’s rev range in one gear under full load, engine power and torque curves can be plotted. If you want to understand power changes, for example, after engine modifications have been made, then a dyno is an excellent tool to have.

Unfortunately, a dynamometer is a professional workshop machine – not one affordable by amateurs! So while I wanted one, nothing came of it – that is, until one day I spotted a second-hand dynamometer for sale. It was being sold without any control gear (and control gear is where electronics really comes in) and so the price was low – very low.

I hired a car-carrying trailer – a dyno’s heavy rollers and stiff frame are a substantial load – and got the machine home. Some hours later, after laboriously using an engine crane and a hydraulic jack to move it, the dyno was off the trailer and in my home workshop. But now what?

Eddy current retarder DC supply

Dynamometers don’t actually measure power, but torque (and also speed – or to be precise the angular velocity of the rollers driven by the car wheels – see the box opposite). To measure torque, the dyno’s rollers are braked. Some simple dynos use disc brakes, but more sophisticated ones like mine use an eddy current brake – usually called an ‘eddy current retarder’.

The eddy current retarder consists of a stator and a pair of rotors. The rotors are shaft connected to and rotate with the dyno’s pair of rollers, while the stator – which contains multiple electrical coils – is attached to a torque arm. When electrical current is passed through the stator coils, eddy currents are generated in the rotors. These eddy currents create a braking force, causing the stator to attempt to rotate with the rotors. However, The torque arm

Fig.1. Bringing the dynamometer (rolling road) home. A second-hand unit, it was bought cheap, but without any power and control electronics.

Power, torque and speed

Readers of *PE* will be familiar with how to calculate electrical power from current and voltage. Leaving aside the subtle effects of phase in AC systems, the calculation is simple: $P = V \times I$. In rotating mechanical systems there is an equally straightforward relationship: $P = T \times \omega$, where P is power, T is torque and ω is rotational speed.

There is one small, but important complication. For the above equation to work the rotational speed (ω) must be measured in radians per second (there are 2π radians in one, full 360° rotation). The speed measurement system receives a pulse train of frequency f from the toothed wheel with n teeth. If there are n pulses per rotation from the wheel then the rotational frequency of the wheel is f/n Hz. To convert this to angular velocity we multiply by 2π. So the final calculation is given by:

$$\omega = 2 \times \pi \times f/n$$
$$= 6.282f/n \text{ (rad/s)}$$

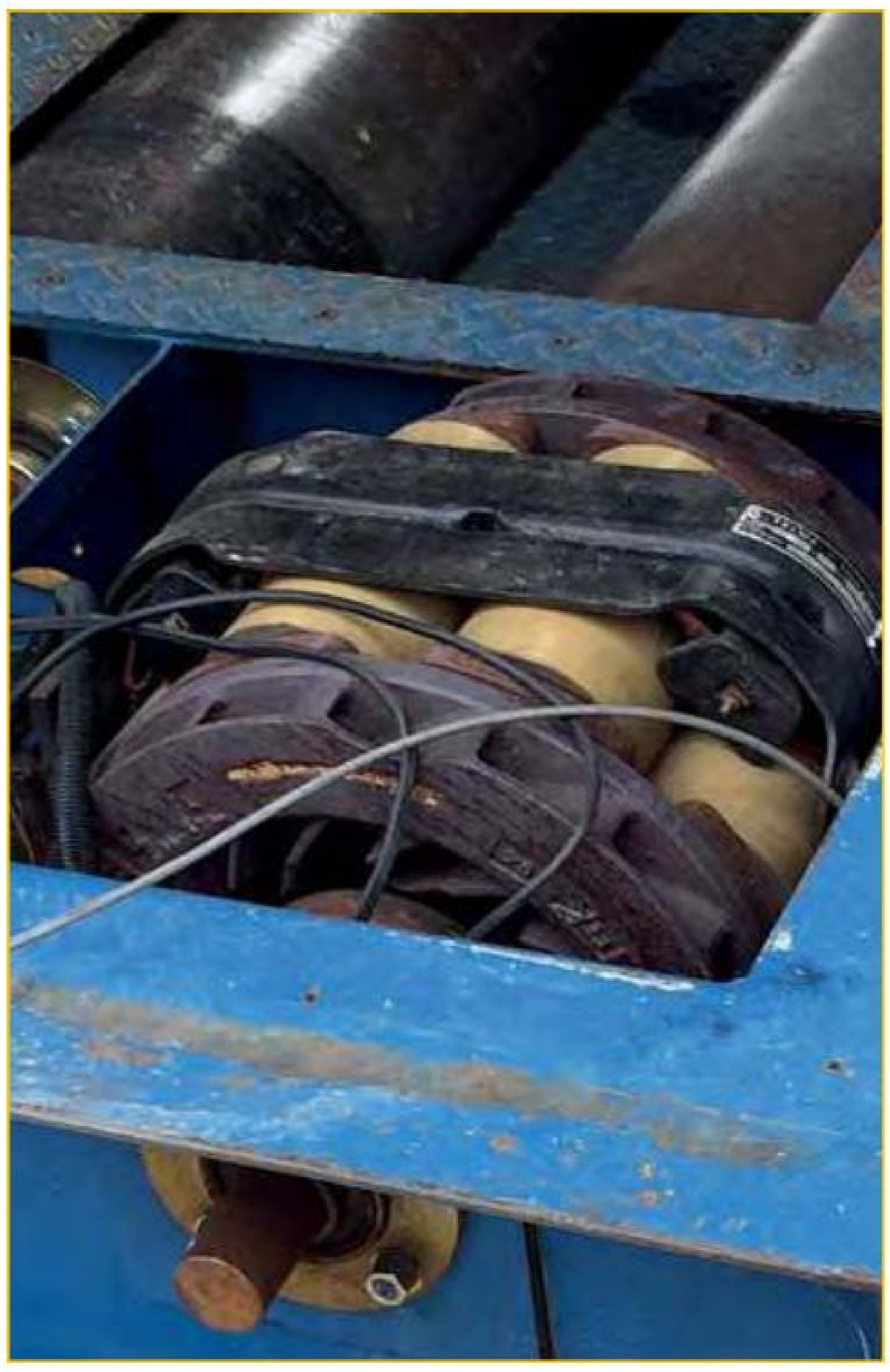


Fig.2. Dynamometer eddy current retarder: the tan cylinders are stator coils, the vented discs are rotors, the end of the system shaft is lower left and the rollers are at the top.

prevents this rotation. The resultant force developed in the torque arm to oppose the stator's rotation is measured by a load cell positioned at the end of the torque arm. This force can be used to directly infer the torque. (For a fuller explanation, there is a nice animation here: **http://bit.ly/pe-aug19-dyno** – the commentary is curiously computerised, but the description is helpful!)

Almost all retarders used in dynos are based around the retarders originally developed for use in trucks and buses. In the vehicle application, the retarder is bolted behind the gearbox and is used as a dynamic brake; eg, down long hills. The vehicular pedigree of retarders means they are wired for use with 12V or 24V DC supplies. For example, the Telma CC135 retarder uses 16 coils, each with a resistance of 0.75Ω. It is designed for 12V operation, and in this form, with all the coils connected in parallel, it will draw 256A:

$$I = V/R = 12 / [1/(1/R1 + \ldots + 1/R16)]$$
$$= 12 / [1/(1/0.75 + \ldots + 1/0.75)]$$
$$= 12 / [1/(16/0.75)]$$
$$= 12 \times 16 / 0.75 = 256\text{A}$$

To use this retarder as a dyno brake, we would therefore need a power supply capable of 256A at 12V. That's difficult to provide, but what if we change the wiring approach? If the retarder coils are instead connected in series, then the total resistance will be 16 × 0.75Ω, or 12Ω. If we use a 192V supply, we'll have the same 12V across each coil as before, but the total current will be only 16A.

It is common practice to change the retarder's coil wiring from parallel to series, and then use a high voltage, variable DC supply. In fact, that is exactly how the eddy current retarder in the dyno I purchased had been configured. The question now was how to provide it? Plus, it isn't enough to simply provide 192V; I needed to be able to change the (average) voltage to vary the average current supplied, thereby controlling the eddy current braking torque.

Commercial DC power supplies designed for use with eddy current retarders are available, but at much too high a cost for me. I therefore developed my own – and it actually proved relatively cheap and easy to do.

Rectifier control

Two main components were used – an IXYS VHF28-16I05 half-controlled, single-phase rectifier bridge, and a United Automation AFM-11 trigger module. The rectifier bridge is rated at 32A and has a freewheeling diode to cope with back EMF spikes. (Spikes can be considerable from the inductance of the multiple retarder coils.) The AFM-11 trigger module uses a 0-5V control input to vary its phase angle, and thus the DC output of the bridge module. (Incidentally, a 'half controlled' rectifier uses two thyristors and two diodes, rather than the four thyristors of a 'full control' device.) The AFM-11 module also has soft start and current-limiting functionality – neither is used in this application. Power supply for the AFM-11 is 18V AC, which is provided by a transformer. I also added a hefty filter to prevent noise being transmitted back into the mains.

I initially mocked-up the system on a piece of board, with the 0-5V control input being achieved by a simple pot. Given that the price of my power supply was about one quarter the cost of the commercial unit, I was very excited to see if it would work. I placed a car on the dyno and raised engine speed to about 2000 rpm in second gear. I then gradually wound up the control pot as I pushed down on the accelerator pedal. And the power supply worked – the dyno load could be smoothly varied using the control knob.

With the power supply proved, I then built it into a heavy-duty plastic box. I added a heatsink for the bridge module, an LED heatsink temperature display,

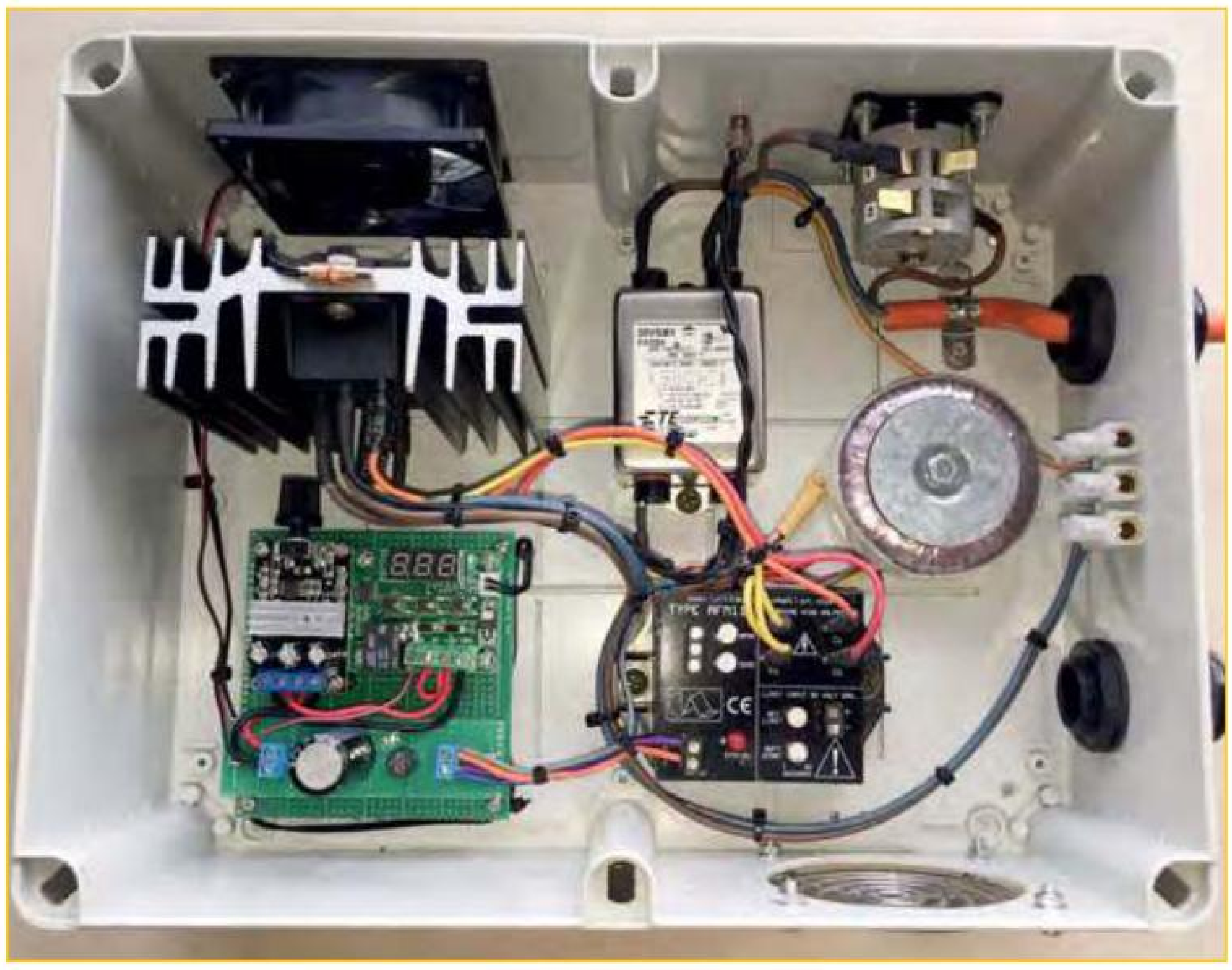


Fig.3. The 0-200V DC, high-current power supply built for the dyno's eddy current retarder. The main components are an IXYS VHF28-16I05 half-controlled, single-phase rectifier bridge, and a United Automation AFM-11 trigger module. Automatic fan cooing is used and the heatsink temperature is displayed. A clear lid is used over this box.

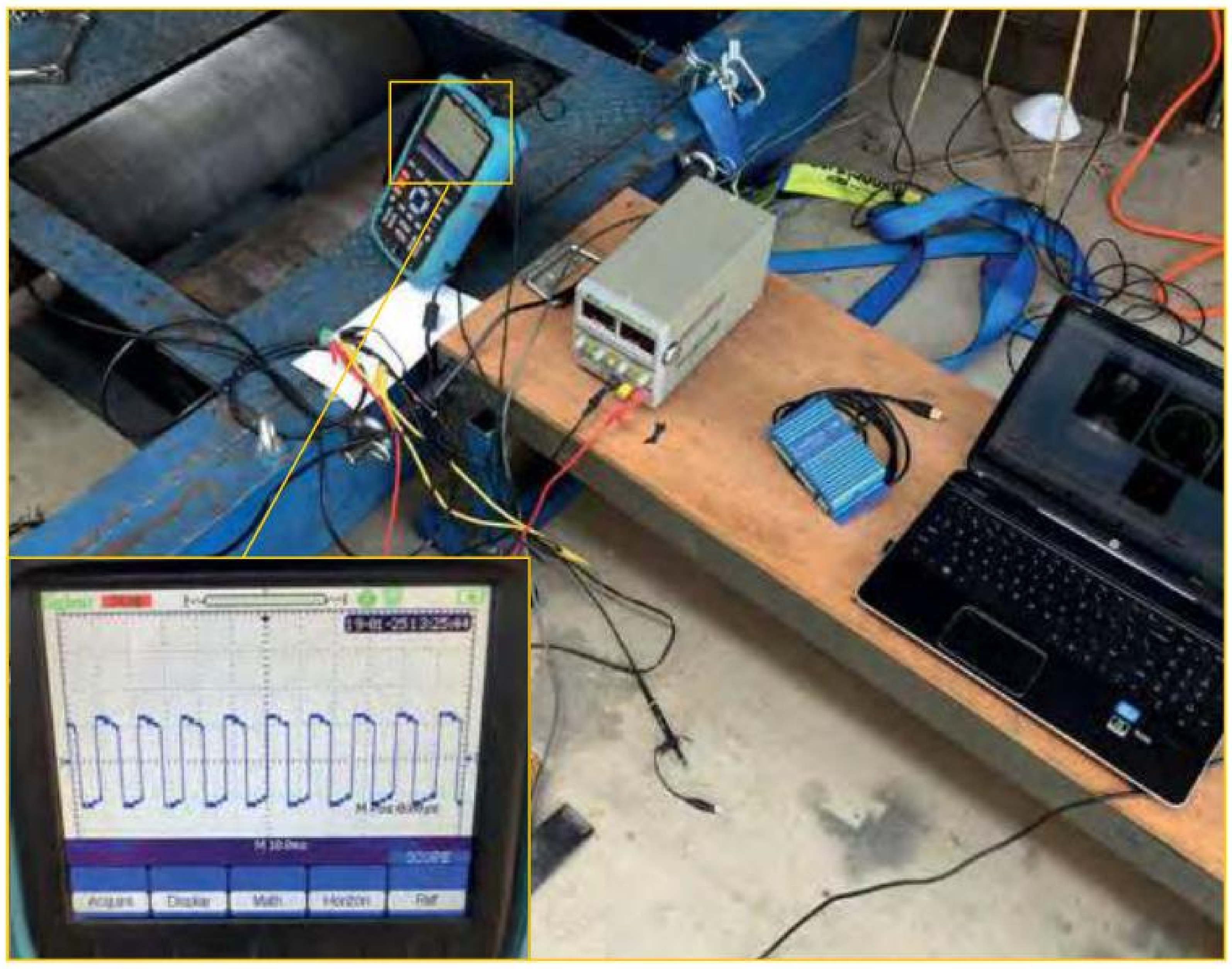
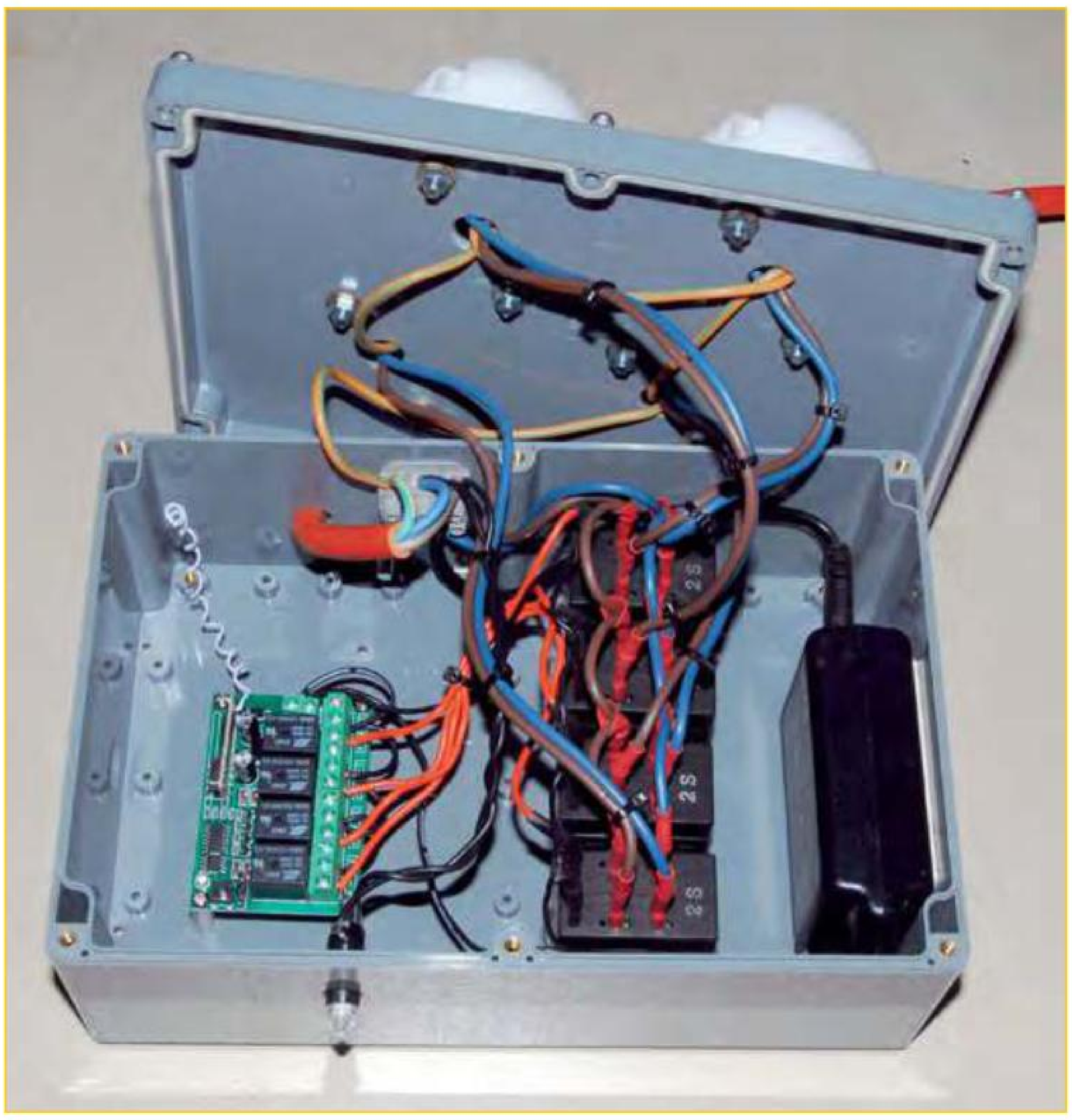


Fig.4 Setting up the dyno speed sensor. The YourDyno control system is the small blue box between the power supply and laptop. I used a non-standard tone wheel and was concerned it might not generate a good signal. However, the inset portable 'scope display shows the excellent square wave achieved from the sensor/wheel combination.



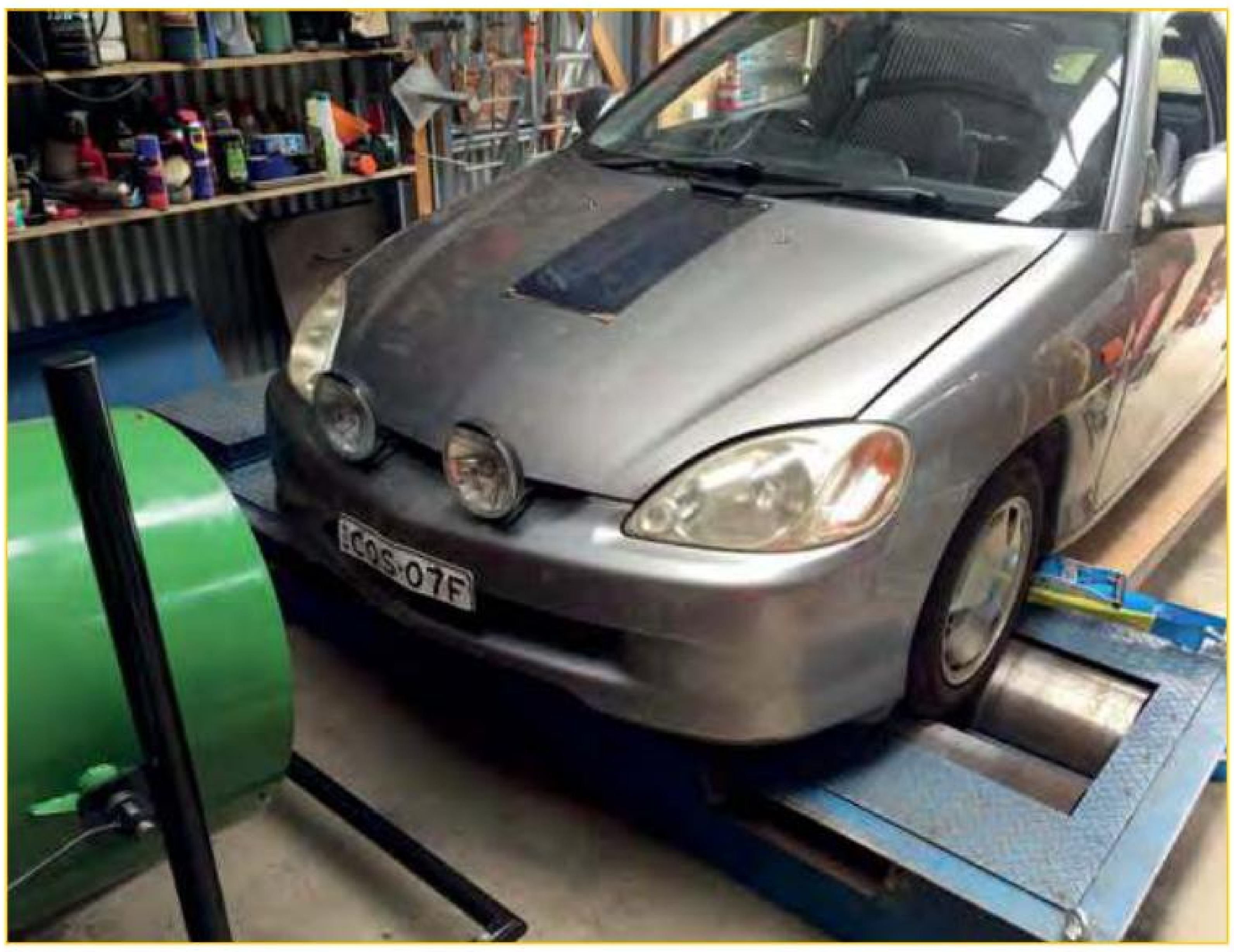


Fig.5. (left) This control box allows remote switching of four mains power outputs. From left to right: the remote control board, four heavy-duty mains relays, and the 12V power supply. The box is used to switch cooling fans from within the car being dyno'd.

Fig.6. (above) The author's Honda Insight on the dynamometer. At left is one of the cooling fans; here directed at the car's radiator.

and an automatically switched cooling fan. A heavy-duty on/off switch was provided, plus a 15A power supply cable to a dedicated 15A power mains outlet. Next, I needed to work out how to measure, log and display power and torque.

Control and measurement system

As explained in the box, to measure an engine's power you only need to know the values of torque and speed. However, to draw graphs of power and torque; automatically control dyno 'ramp rates' (the rate at which the dyno accelerates through the rev range); and log other data like intake manifold pressure, places high demands on a control and logging system.

After considering lots of options, I decided to go with a Norwegian product – YourDyno. This neat package has been developed by one man – Jostein Fonneland – and comprises both hardware and PC software. The small hardware box is powered by the USB port of the PC to which it is connected. The system generates a 0-5V output signal that controls the retarder's DC power supply – perfect. It requires signal inputs from the strain gauge that is measuring the force developed on the end of the torque arm, and dyno roller speed. Now, how to provide those signals?

Connecting the strain gauge (sometimes called a load cell) was straightforward. These devices comprise a four-wire Wheatstone bridge. An excitation voltage is applied, and output voltage varies with strain. S-type strain gauges are most often used in dyno applications – these can measure both compression and extension. The voltage output

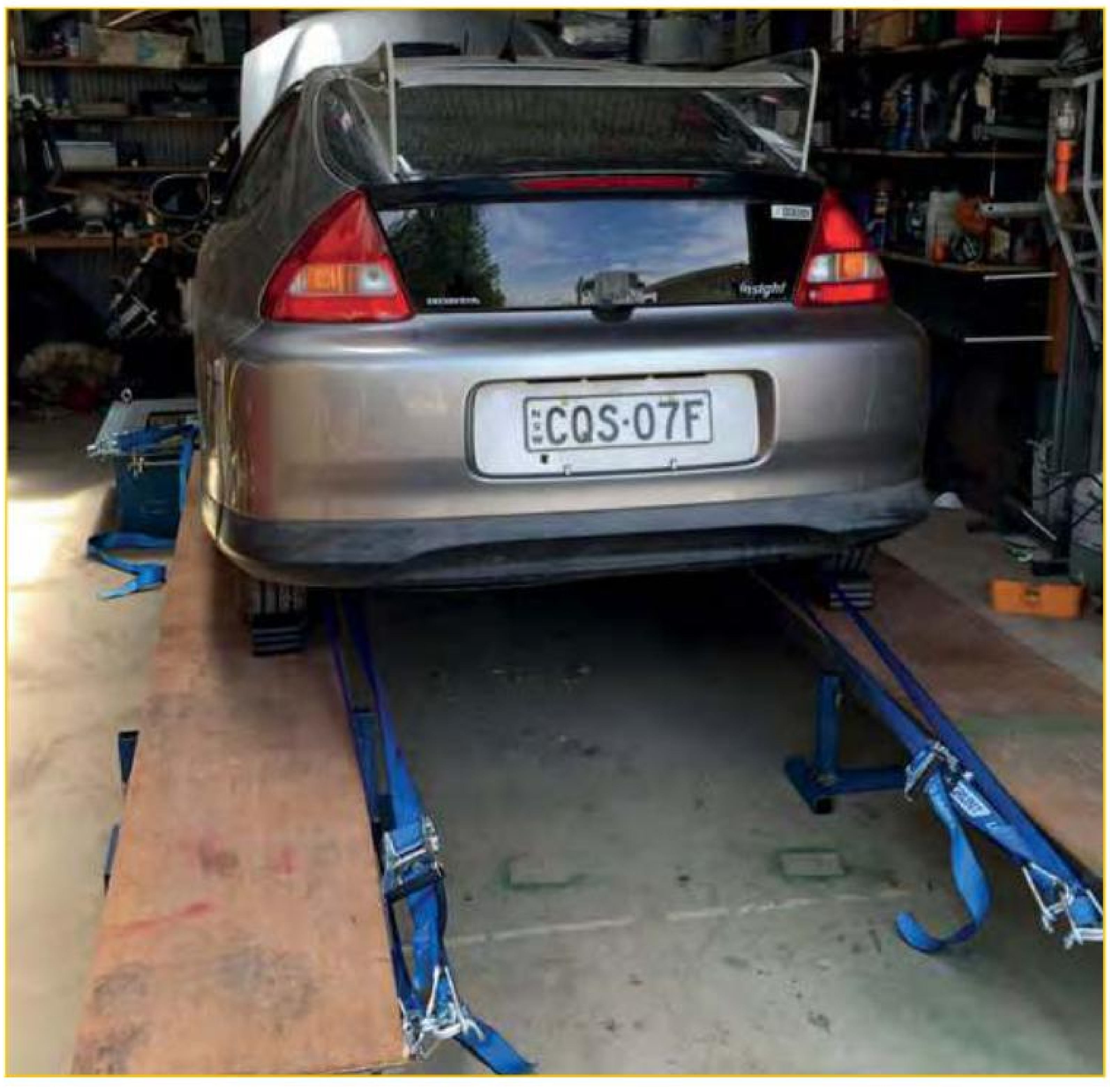


Fig.7. The rear view. Straps prevent the car moving longitudinally and laterally. When being tested, the car climbs the front set of rollers, which are knurled to prevent slip.

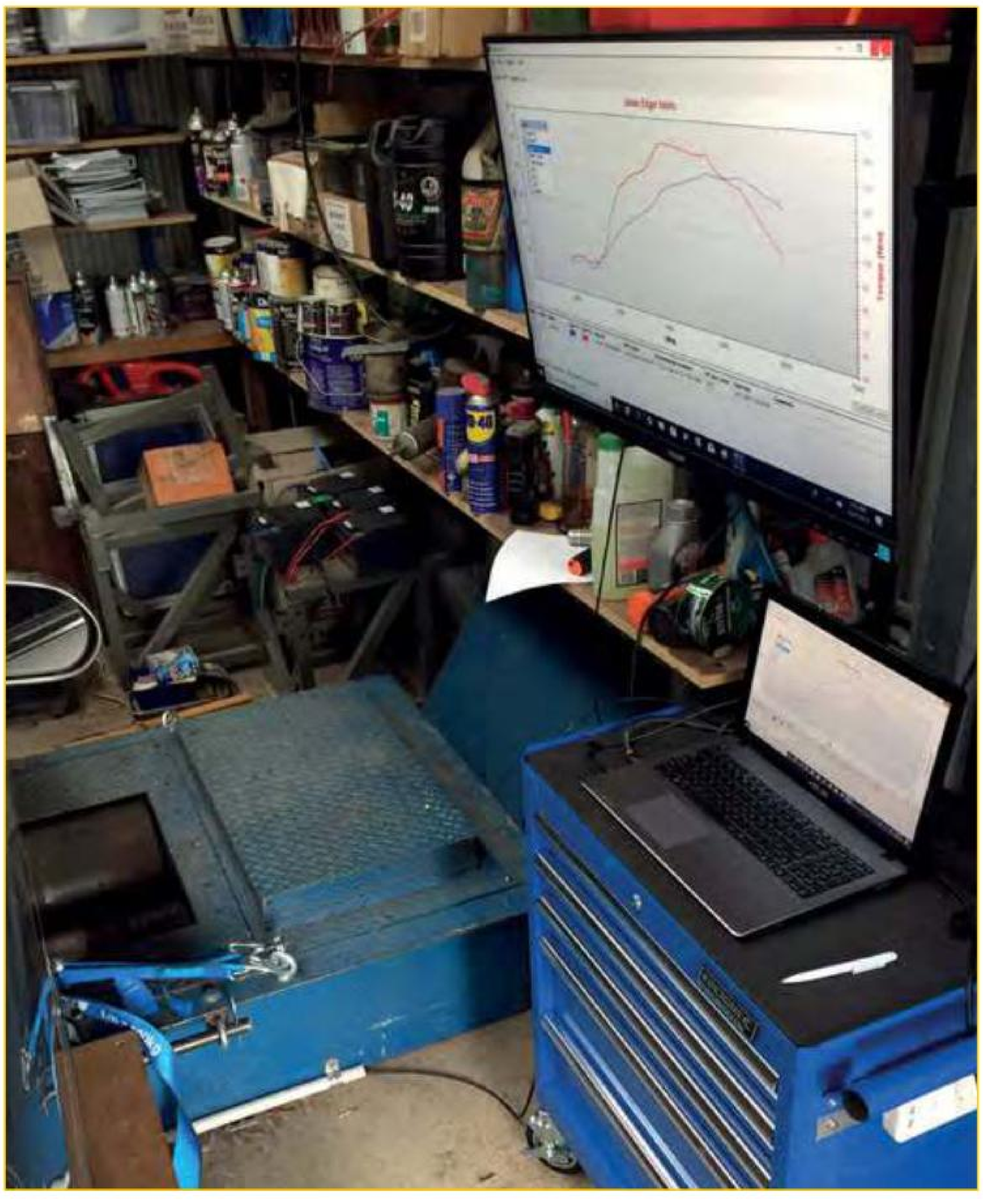


Fig.8. View of the dyno displays. The laptop is on top of the tool trolley, with a larger repeating screen located above. The car (just visible to the left) is strapped to the dyno frame.

of the sensor is very low (typically 1-3mV per volt of excitation) and so needs to be amplified. The YourDyno controller has such an amplifier built-in. Interestingly, the colour codes used in strain gauge wiring are much the same across different manufacturers, making the wiring easy.

My dyno came with an S-type strain gauge installed, and I easily calibrated it in the YourDyno software. This process requires entering into the software the length of the torque arm, and then applying different weights to the torque arm directly above the strain gauge. I found it best to get different people to stand on one foot, their weight being borne by the strain gauge. After being zeroed at no load, only one weight value needs to be input, but other weights can be used to test for sensor linearity.

Now, what about roller speed? Roller speed is sensed by a toothed wheel, with the teeth rotating past an inductive sensor. Here I took a risk. The YourDyno technical information has very specific shape requirements for the toothed wheel – but to fit such a wheel, I'd have to get the wheel made and then pull half the dyno apart to be able to fit it to a shaft. Instead, could I use the YourDyno sensor with the existing wheel – even though its teeth were not of the specified profile? I tried it and measured an excellent quality square wave output from the sensor – and the YourDyno controller was equally happy with it.

So, were we all set to go? Here's where it will become clearer why I went for YourDyno rather than attempting to build my own controller/logger.

Operation

A typical dyno run starts by holding the engine at a fixed speed (eg, 1500 rpm) at full throttle. The software then reduces the load and allows the engine to accelerate through to the redline, constantly changing load so that the rate of increase is smooth and linear, even with variation in engine torque. To do this, it needs to control dyno speed accurately – and to achieve that requires the use of a full PID (proportional, integral, derivative negative feedback) software controller. In addition, as the engine is accelerating, some resistance is caused by the dyno rollers' inertia – and if the measurements of torque and power are to be correct, this needs to be compensated for.

Speed and load data also needs to be appropriately filtered and logged, and then displayed in graphical form, preferably with multiple runs being overlaid to enable comparison. Finally, the readings need to be corrected for variations in ambient temperature and pressure – something that can be achieved automatically with the atmospheric sensors built into the YourDyno controller.

While YourDyno is nowhere near as capable as professional-level dyno hardware and software, it's vastly cheaper – and in my experience, works very well.

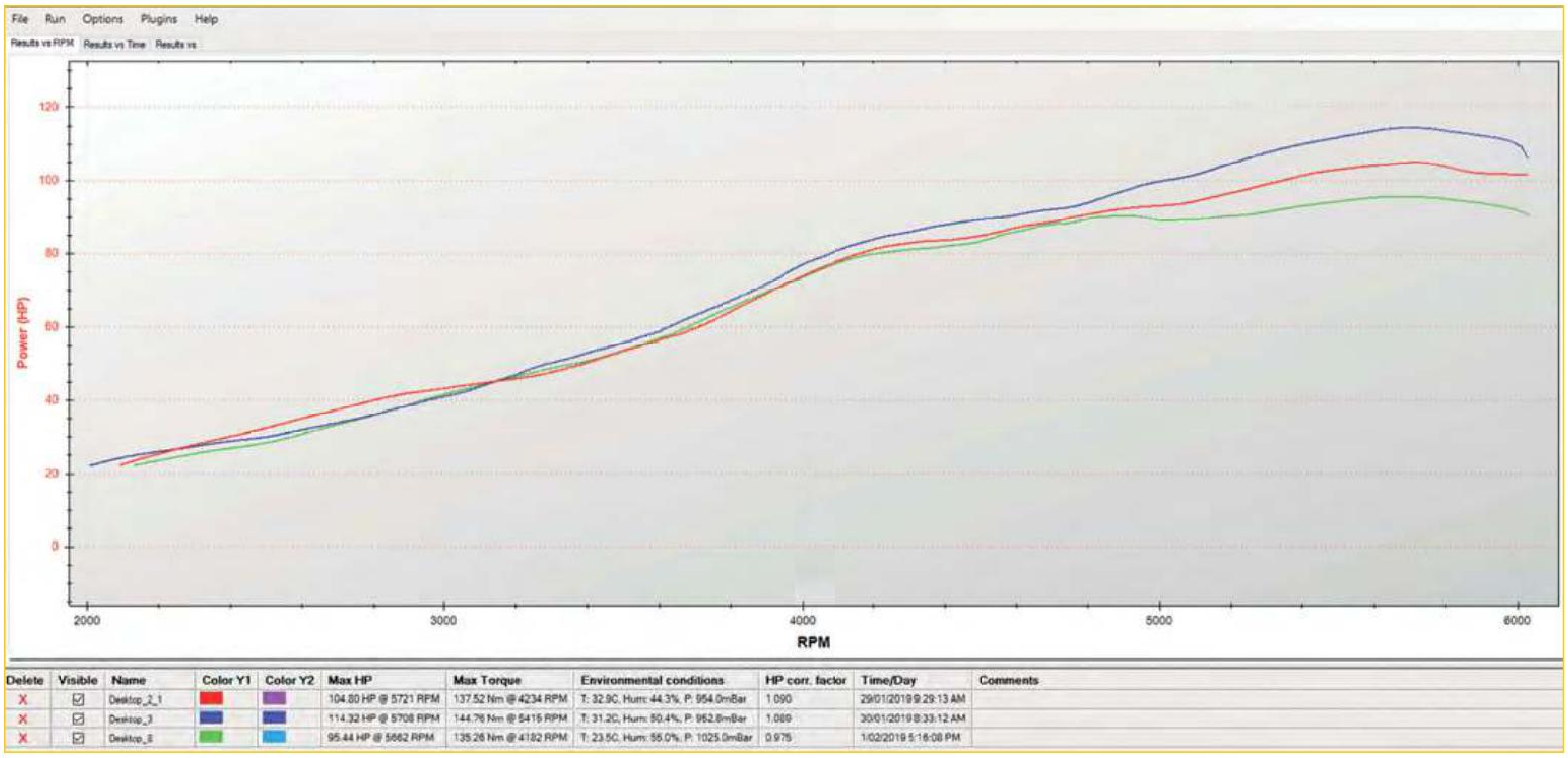
Controlling the dyno systems from the car

It's important that everything can be controlled by the person 'driving' the car on the dyno. However, I didn't want the dyno laptop in the car, as there is often another laptop PC being used to program the engine management. But, if I use a laptop as the dyno control PC placed outside the car then its screen is too small to be clearly seen while seated in the car. I therefore added a large additional monitor for the dyno. It is supported by an arm at an appropriate height to be viewed through the side window of the car. Control of the YourDyno software is achieved using a Bluetooth remote keyboard with an inbuilt mouse pad.

I made one further improvement – I soon found it annoying that I couldn't control three important fans from within the car. The fans used are: a large front fan to cool the radiator, a large rear fan to move exhaust gases out of the workshop, and a small blower connected to a hose to cool specific engine bay components. Often, when sitting in the car, I wanted to switch on or off one or two of these fans. To achieve remote switching, I built a box containing four heavy-duty mains relays, the relays controlled by a low-cost four-button eBay remote control module.

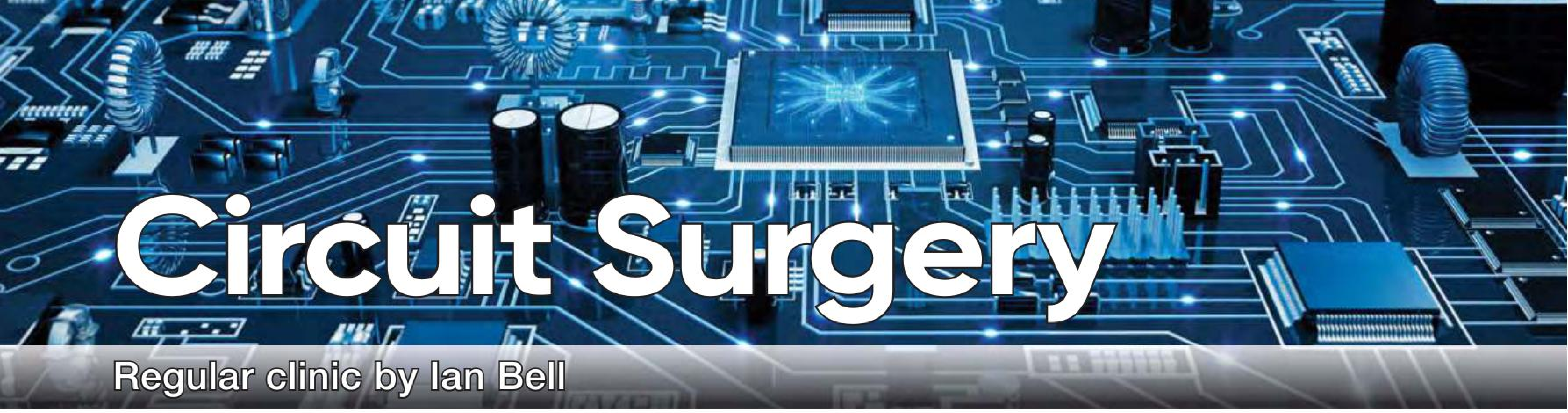
Conclusion

A home dyno is certainly not for everyone – and I am sure that my (relatively distant) neighbours are glad I don't run it for more than an hour or two every few weeks. But what I think makes this an intriguing story for an electronics magazine is the sheer amount of low-cost DIY electronics involved. In short, there's never been a better time to enjoy electronics while modifying cars!



Delete	Visible	Name	Color Y1	Color Y2	Max HP	Max Torque	Environmental conditions	HP corr. factor	Time/Day	Comments
X	☑	Desktop_2_1	🟥	🟪	104.80 HP @ 5721 RPM	137.52 Nm @ 4234 RPM	T: 32.9C, Hum: 44.3%, P: 954.0mBar	1.090	29/01/2019 9:29:13 AM	
X	☑	Desktop_3	🟦	🟦	114.32 HP @ 5708 RPM	144.76 Nm @ 5415 RPM	T: 31.2C, Hum: 50.4%, P: 952.8mBar	1.089	30/01/2019 8:33:12 AM	
X	☑	Desktop_8	🟩	🟦	95.44 HP @ 5662 RPM	135.26 Nm @ 4182 RPM	T: 23.5C, Hum: 55.0%, P: 1025.0mBar	0.975	1/02/2019 5:16:08 PM	

Fig.10. A screen grab from the YourDyno software. Engine power (measured at the wheels) is shown for three different states of tune. Note the data below the graphs that shows maximum power and torque, and the environmental conditions and date/time for each run.



Circuit Surgery

Regular clinic by Ian Bell

Understanding bipolar junction transistors – Part 2

Last month, in response to both recent and older questions on the EEWeb forum, we started looking at the different ways bipolar transistor circuits can be configured – common emitter, common base and common collector. These are three of the arrangements in which transistors are used, and on which amplifiers and other circuits are based. This month, we will look at the common-emitter amplifier in detail, but our coverage of the basics of bias and the use of models to analyse circuits is relevant to working with all the configurations. The basic concept of transistor configurations is illustrated in Fig.1. These are not circuit schematics, they just illustrate the orientation of the transistor in circuits of each type and apply to both NPN and PNP transistors.

Common emitter

The most basic NPN implementation of the common-emitter amplifier is shown in Fig.2. This takes the concept shown in Fig.1 and adds a resistor (R_1) between the collector and the power supply. A connection with a supply is essential – amplifiers use energy from the power supply in order produce output signals with more power than their input signal. The collector resistor also converts the varying collector current (transistor output) into a varying collector voltage. More specifically, variation in the input voltage, which is equal to the transistor's V_{BE}, will result in a variation of collector current (I_{C}) which will cause variation in the voltage dropped across R_1, and hence variation in the output voltage.

Last month, we looked at some of the theory of transistor operation and the models which are used in calculations, simulation and circuit design. We discussed the simplified Ebers-Moll model for the transistor, and the relationship between emitter current and base-emitter voltage:

$$I_E = I_{ES}\left[\exp\left(\frac{V_{BE}}{V_T}\right) - 1\right]$$

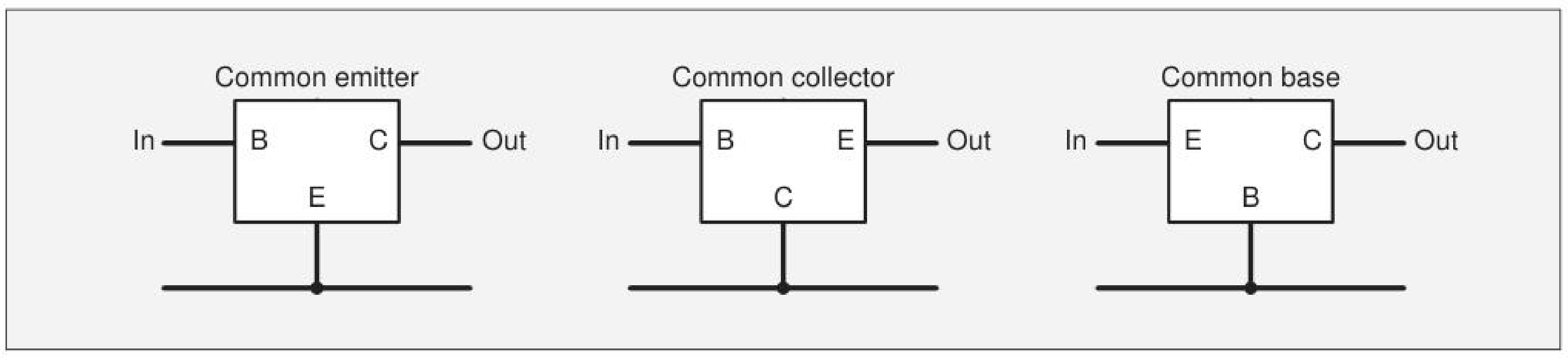


Fig.1. Transistor configurations – these concepts apply to both NPN and PNP. Actual circuits require additional components.

Here, V_{T} is the 'thermal' voltage – a parameter which appears in many semiconductor equations and which has a value of about 25mV at around 20°C. I_{ES} is the base-emitter junction saturation current – a parameter specific to the particular transistor.

Exponential relationship

The emitter current equation shows that the relationship between the base-emitter voltage and collector current is exponential – this term of course has a specific mathematical definition, but even in everyday language it is well-known, meaning something like an increase 'becoming quicker and quicker'. The more we increase V_{BE} the more effect further changes in V_{BE} will have on collector-emitter current. This can be seen in Fig.3, which is a plot of collector current (I_{C}) against base-emitter voltage (V_{BE}) for a typical general-purpose transistor (BC547B). We see little collector current until V_{BE} reaches about 0.6V, after which I_{C} increases rapidly, with the curve getting steeper and steeper as V_{BE} increases.

It is the shape of the curve in Fig.3 that leads to the well-known idea that a transistor 'switches on' for V_{BE} above 0.7V. This is just a rule of thumb, and transistors are commonly operated with V_{BE} in the 0.6V to 0.7V range in general-purpose, lower-power amplifiers. Fig.4 shows a small part of the same curve in Fig.3, which makes the values easier to read. Looking over the whole graph in Fig.4, we see that increasing the base-emitter voltage from 0.60V to 0.68V, a change just of 13% (×1.13) results in a near 20-fold (×20) increase in collector current. Thus, very small changes in input voltage in the circuit in Fig.2 can cause relatively large changes in collector current, and therefore relatively large changes in the voltage dropped by R_1 – that is, relatively large output voltages changes. In this way the circuit

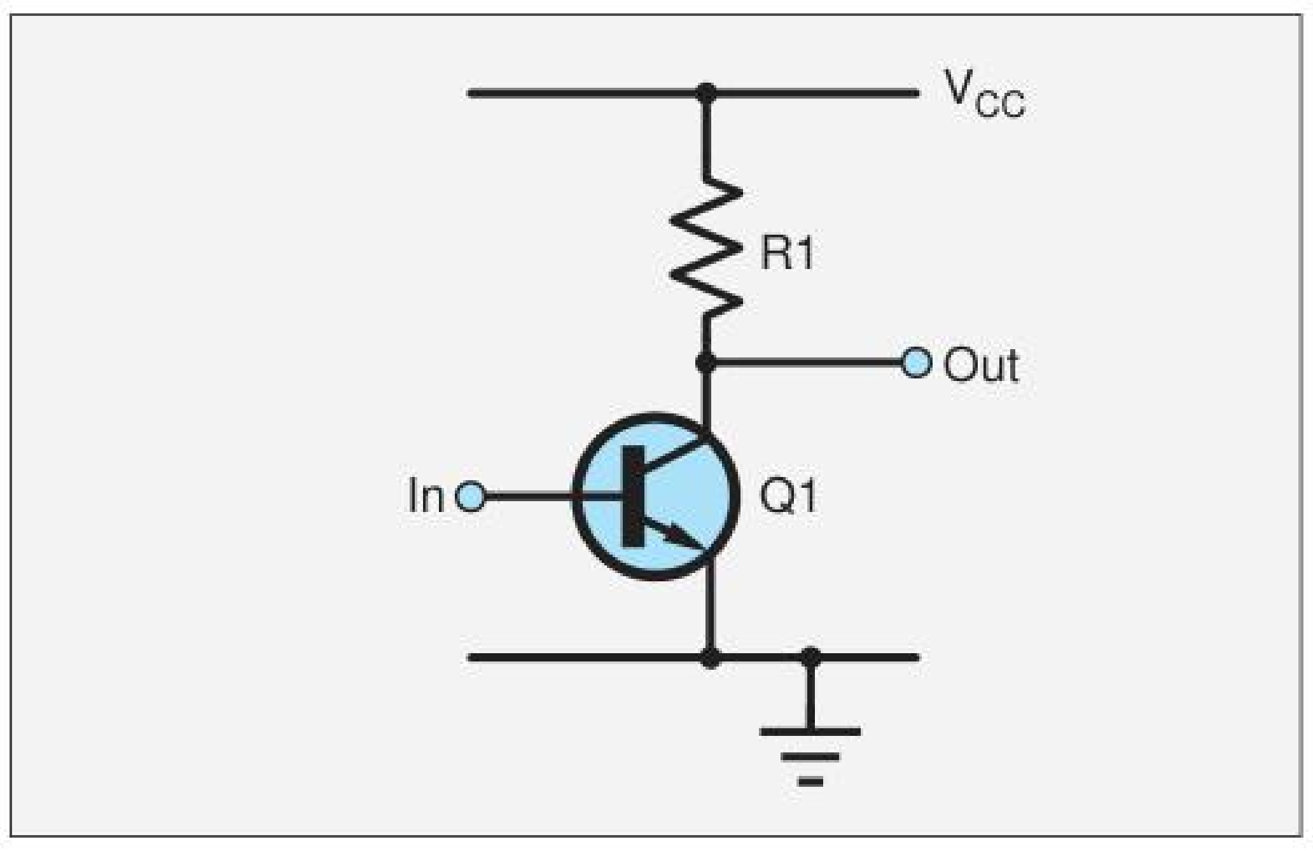


Fig.2. Basic common-emitter amplifier.

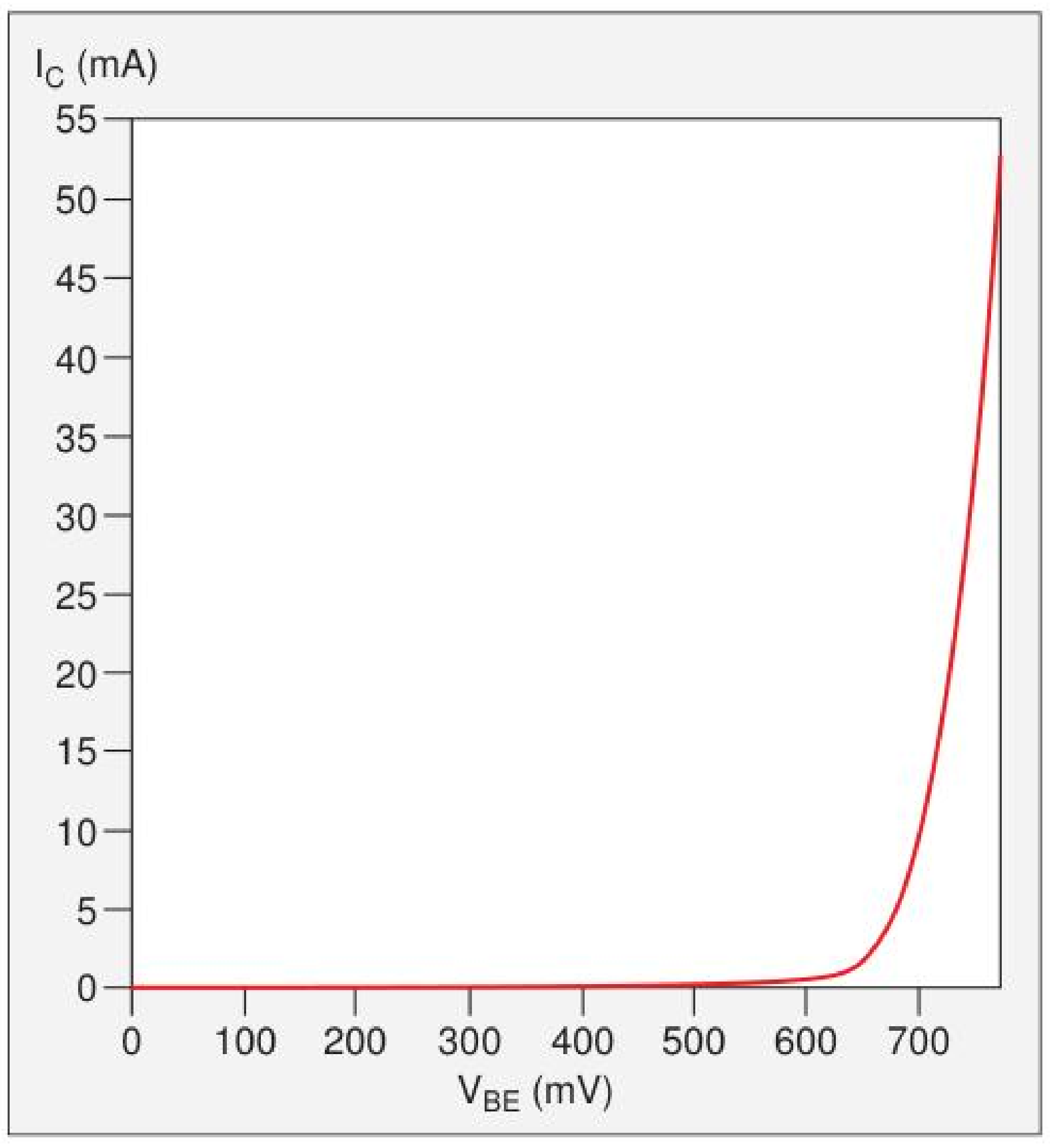


Fig.3. Typical transistor characteristics for I_{C} against V_{BE}.

Simulation files

The LTSpice files discussed in *Circuit Surgery* are available for download from the *PE* website.

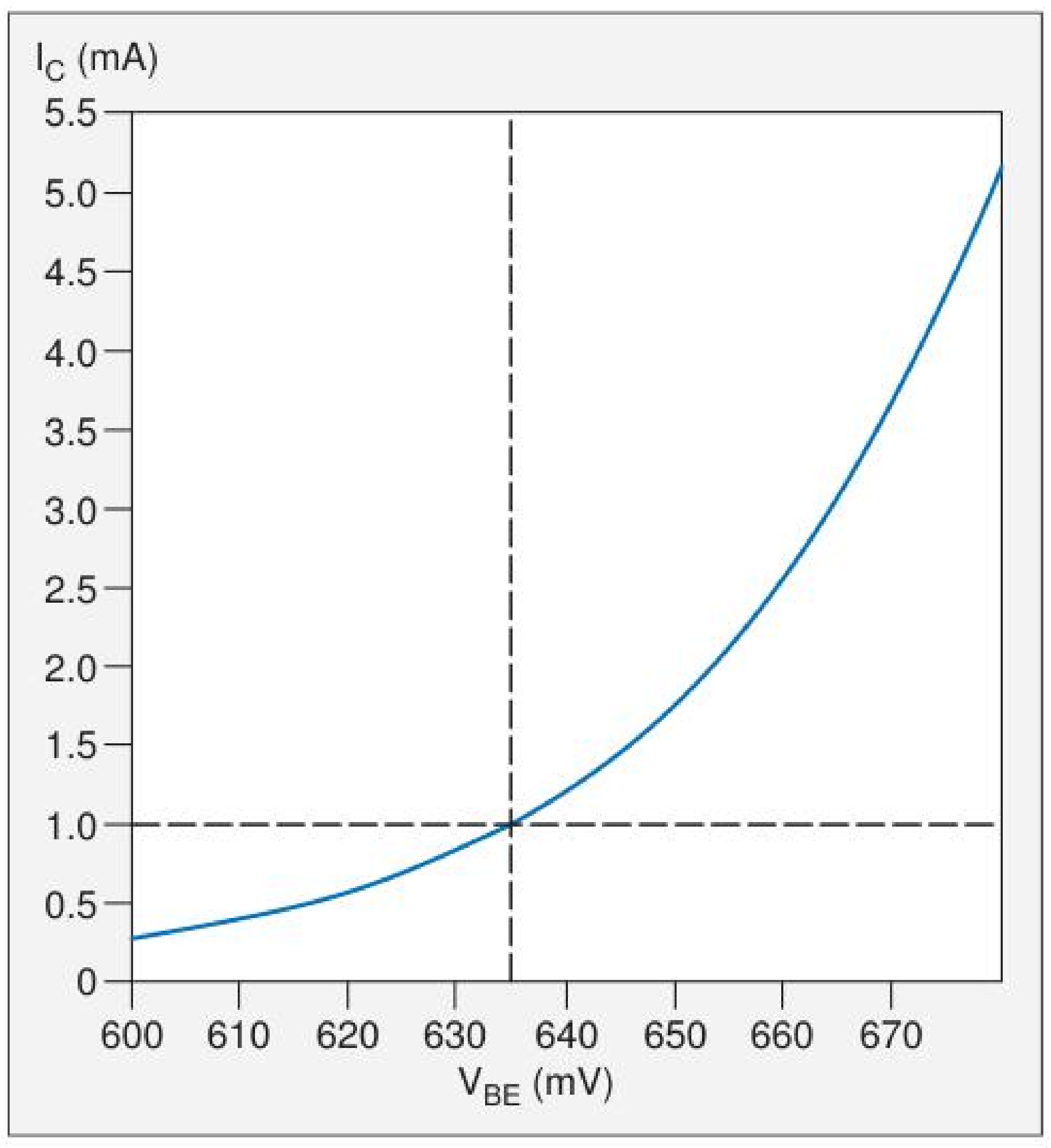


Fig.4. Zoom on part of the curve in Fig.3.

acts as a voltage amplifier with potentially high gain.

From Fig.3 and Fig.4 we see that an increase in input voltage increases the collector current (I_C) and hence the current in R_1 in Fig.2. Ohm's law tell us that this will increase the voltage across R_1. Now, since R_1 is connected to the (positive) supply voltage (V_{CC}), increasing the voltage dropped across R_1 decreases the output voltage, specifically $V_{OUT} = V_{CC} - I_CR_1$. Thus the circuit in Fig.2 is an *inverting* amplifier.

Bias and operating point

For a typical AC amplifier we would expect the input signal to vary around 0V (to be pure AC). Looking at Fig.4, we see that unless the signal is significantly larger than 0.6V the collector current will be very small and V_{OUT} will remain close to the supply voltage. This leads us to the important concepts of bias and operating point. If we add a fixed DC voltage (called the bias) to the AC input signal then we can make the signal cause the collector current to vary around any point on the curve in Fig.3 (called the 'operating point').

Last month, we also mentioned operating points in the context of creating simplified small-signal models, which are easier to use for analysing circuits. The transistor's input-output relationship is non-linear (not a straight line graph) as shown in Fig.3 and Fig.4, but the smaller the range of variation we consider, the closer the curve approximates a straight line. This is illustrated in Fig.5. If we take an operating point of V_{BE} = 0.635V (as indicated in Fig.4), which corresponds to a collector current of approximately 1mA, and just plot the curve for 5mV above and below this point we get Fig.5, which is almost a straight-line graph. Normally, we want an amplifier to be as linear as possible, otherwise our output signal will be distorted (not have the same waveform *shape* as the input). However, here we see that the basic common-emitter amplifier is not particularly linear unless we keep input signals very small. More sophisticated circuits overcome this issue using feedback, which we will discuss later.

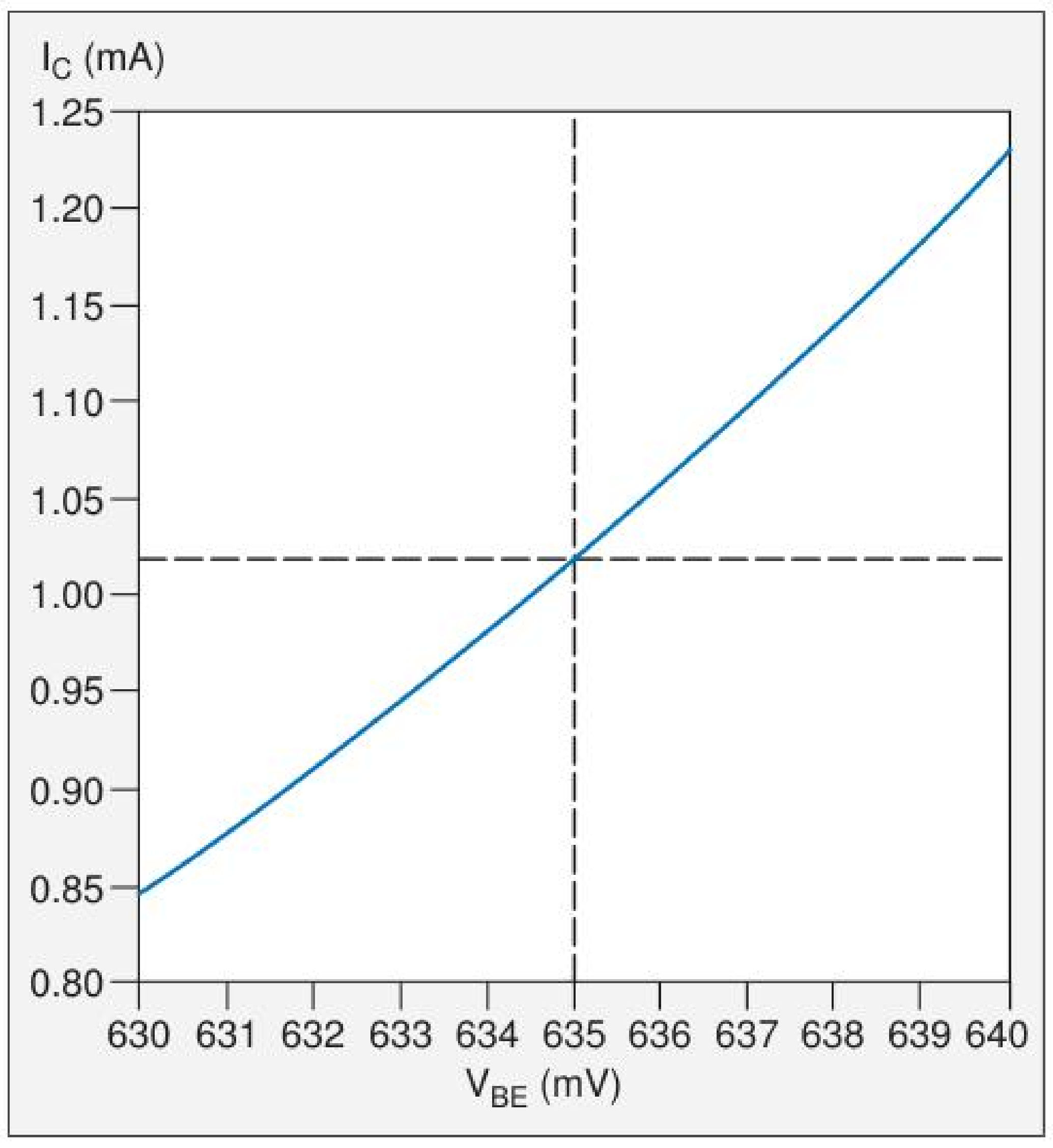


Fig.5. The curve in Fig.4 close to a bias voltage of V_{BE} = 0.635V.

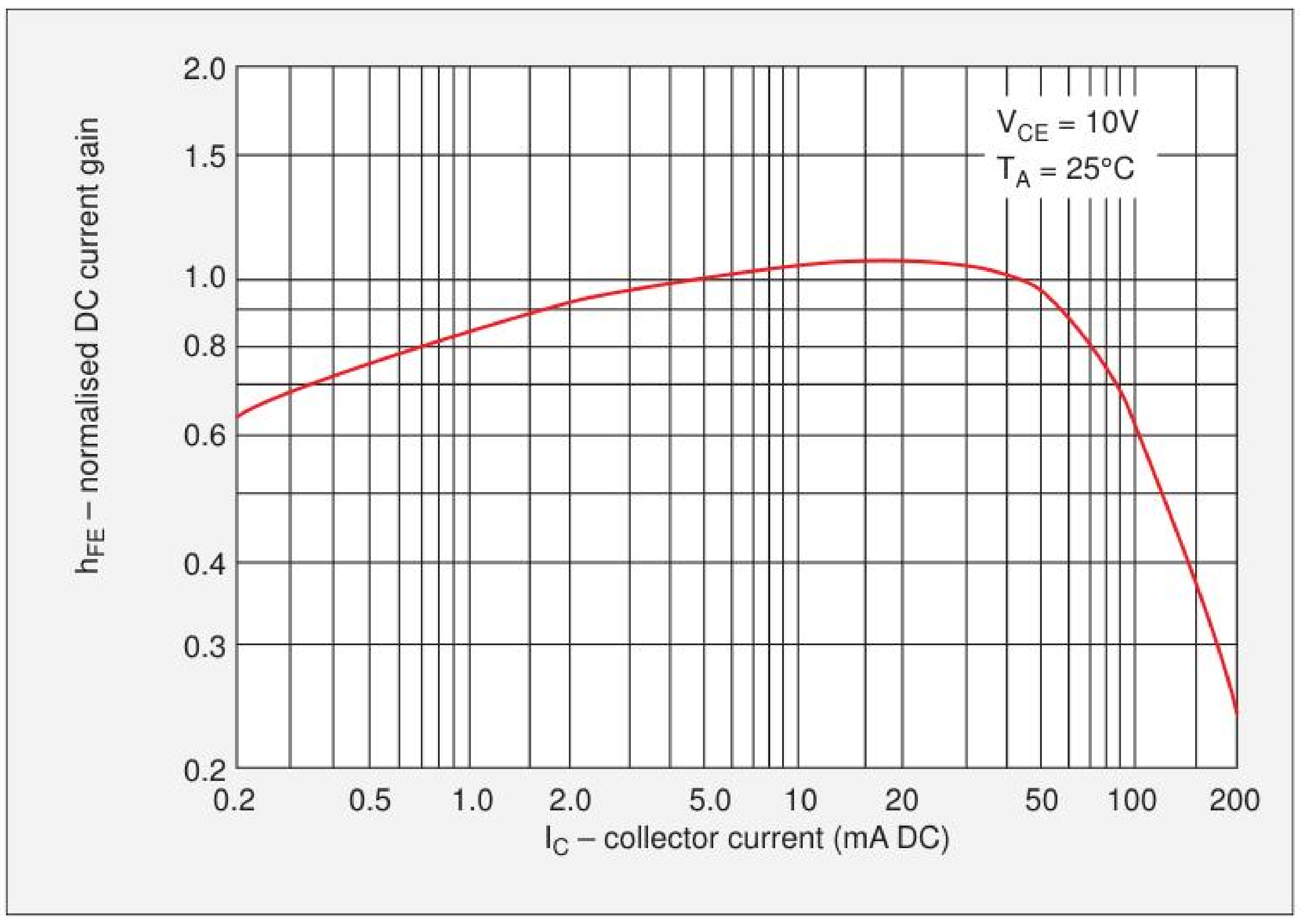


Fig.6. Variation of current gain with collector current for the BC547 (from ON Semiconductor data sheet, **onsemi.com**).

The preceding discussion leads to the question of exactly what operating point we should use, and like most design decisions there are trade-offs. We mentioned in our discussion last month that transistor parameters are not fixed for individual devices, but vary with the operating point. We can see this by looking at datasheet curves; for example, Fig.6 shows the variation of current gain with collector current for a BC547 from ON Semiconductor. We should choose an operating point where parameters of interest are not too far from their optimal values. However there may be other considerations; for example, the higher we set the operating point collector current with no signal present the more power the circuit will consume with no signal present, leading to a less efficient design.

An operating point of I_C = 1mA, as shown in Fig.5, could be considered a reasonable compromise between the smaller transistor gain at lower collector currents (see Fig.6) and reducing power dissipation. This is not a specific recommendation, just an example used here, also motivated by using 1mA as a round number value for I_C. Having chosen V_{BE} = 0.635V as the bias voltage, with the transistor operating at about 1 mA with no signal we can select a suitable value for R_1. Often, we want to make sure an amplifier can output the maximum amplitude signal possible, which is fundamentally limited by the supply voltage. If we use, for example, a supply of 12V (V_{CC} = 12V in Fig.2) and we assume a symmetrical input signal, such as a sinewave, then we would want the output with no signal present to be 6V, allowing the signal to change the output from 0V to 12V (6V peak amplitude). This means R_1 should drop 6V with no signal present, which with 1mA flowing through it requires a value of 6kΩ.

The real situation is a little more complex than this. The output cannot go all the way down to 0V as the transistor enters a condition known as saturation at low collector-emitter voltages where the base current no longer controls the collector current in the same way. This limits the minimum output voltage to something typically in the 0.2 to 0.5V range. However R_1 = 6kΩ is fine for this example and the discussion so far leads to the circuit in Fig.7, in which the bias has been included as part of the input signal – `V1` is a source with a DC value of 0.635V on to which is added a 1kHz 5mV peak sinewave.

Calculating gain

An obvious question is what is the gain of the circuit in Fig.7? We can estimate

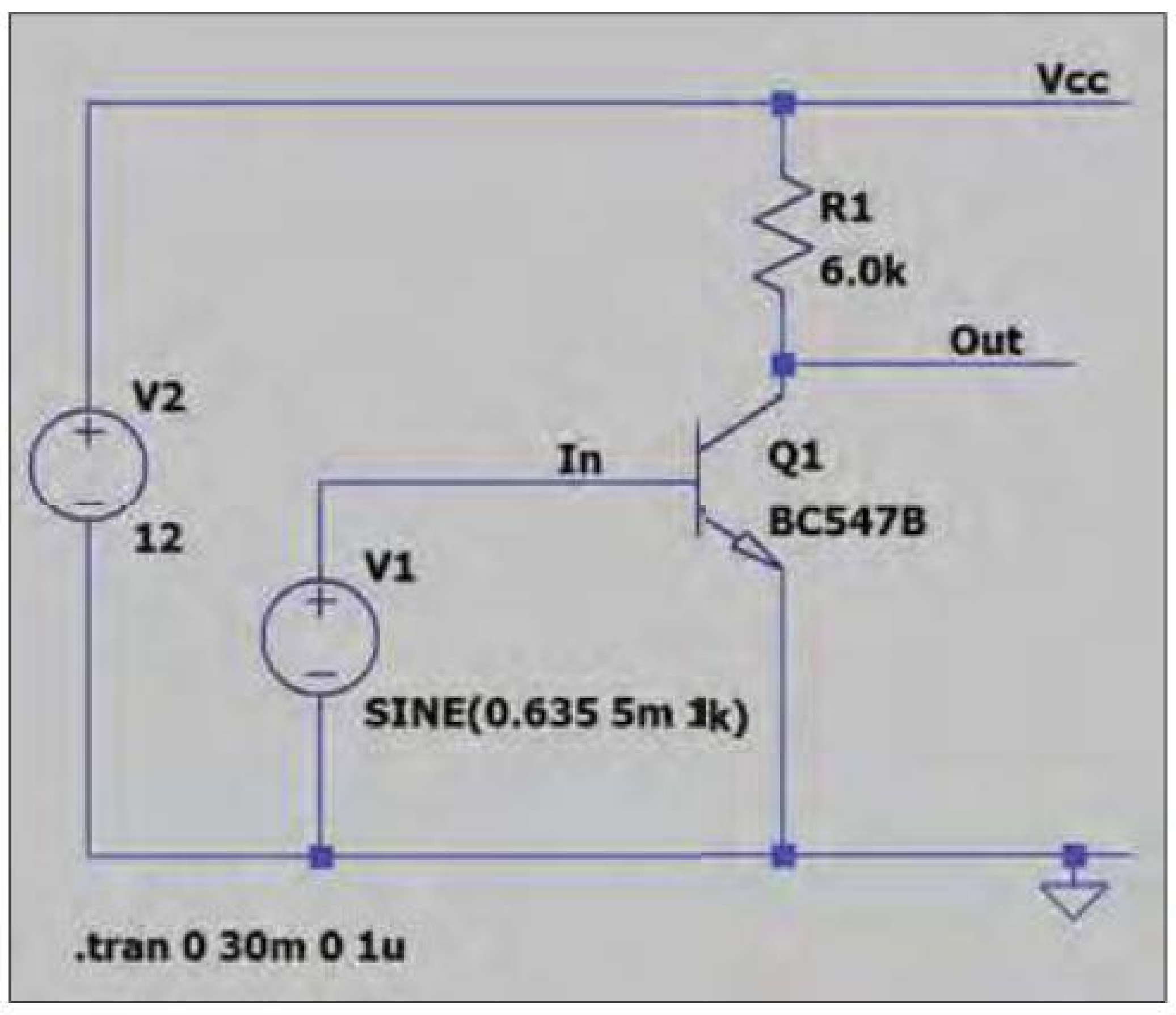


Fig.7. Common-emitter amplifier with bias included in the input signal.

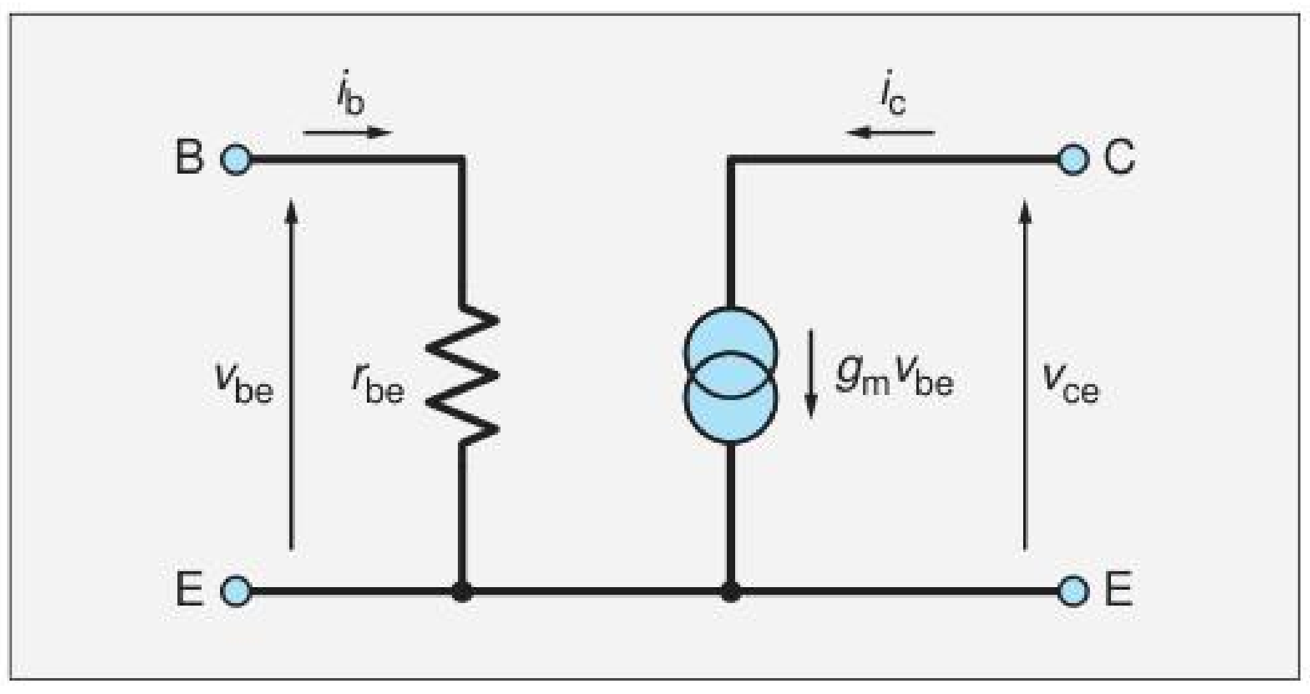


Fig.8. Small-signal model of a bipolar transistor.

this from Fig.5, which shows the input-voltage-to-collector-current relationship at the operating point. A variation of 10mV in the input (V_{BE}) gives a collector current variation of about 380µA, which translates to a variation of 2.3V across the 6kΩ of R_1 and hence at the output. Thus the gain is about –2.3V/10mV, or –230. The negative value indicating an inverting amplifier.

An algebraic approach to the gain calculation involves calculus – differentiating an equation for the input-output voltage relationship of the circuit at the bias point, based on the emitter current equation above inserted in $V_{OUT} = V_{CC} - I_C R_1$. We will not go into the details, but the result is an approximate gain of $-I_C R_1 / V_T$, where I_C is the collector current at the operating point. For our circuit we get (1mA × 6kΩ)/25mV, which is –240 at 20°C – close to our previous estimate. This equation avoids having to use the characteristic curve.

Finally, we can also calculate the gain using the small-signal models discussed last month. Unlike the approach outlined in the previous paragraph we do not have to have to perform calculus on equations specific to an individual circuit, effectively this is already built into the models. We just plug in the relevant models in place of the transistors and remove any DC voltages. Often, this leads to an equivalent circuit which is straightforward to analyse with basic circuit theory. This approach is widely used and you will often find extensive analysis like this in textbooks and online resources related to transistor circuit design. Here we will show one example to illustrate how it works.

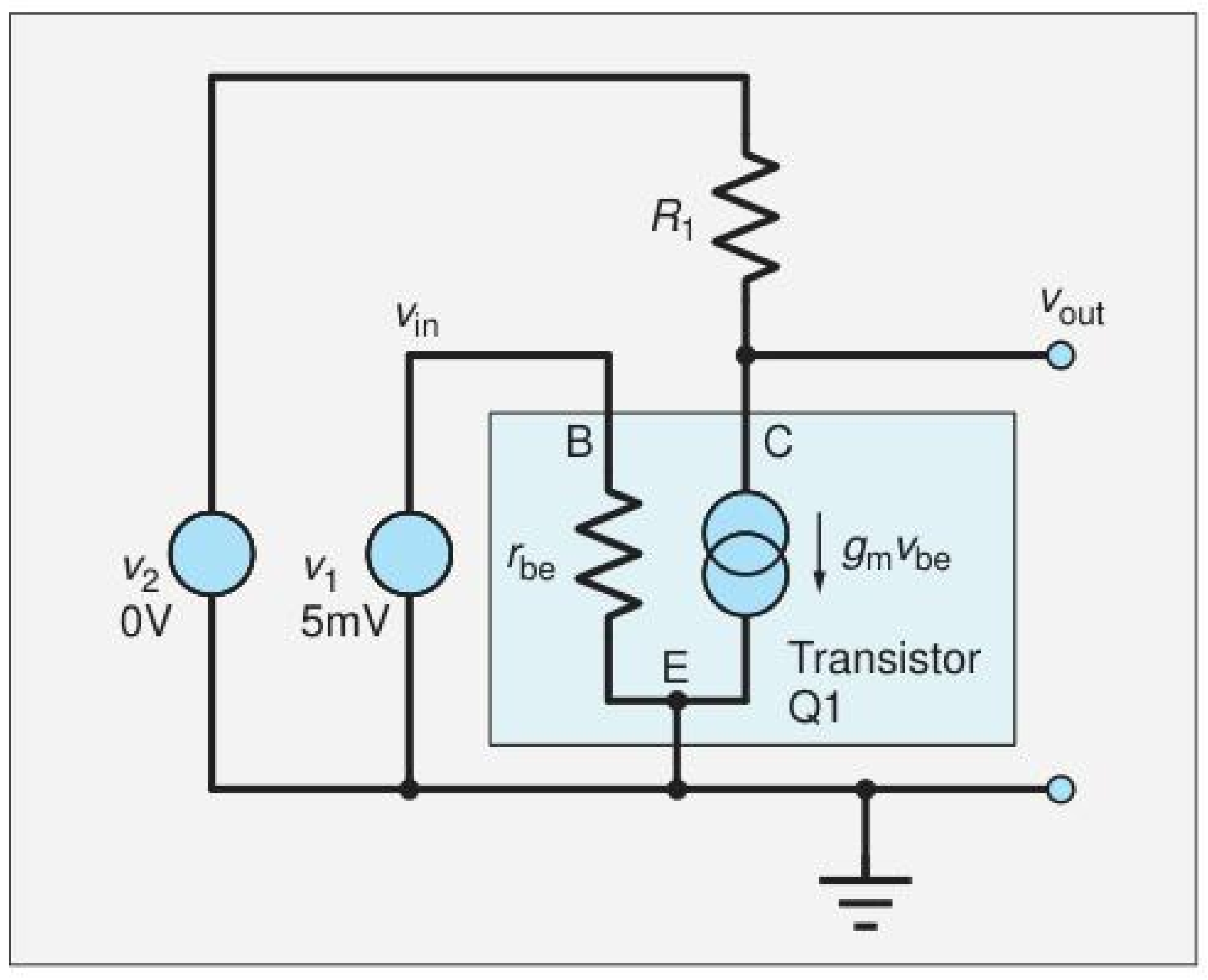


Fig.9. Small-signal model of circuit in Fig.7, drawn with the original layout.

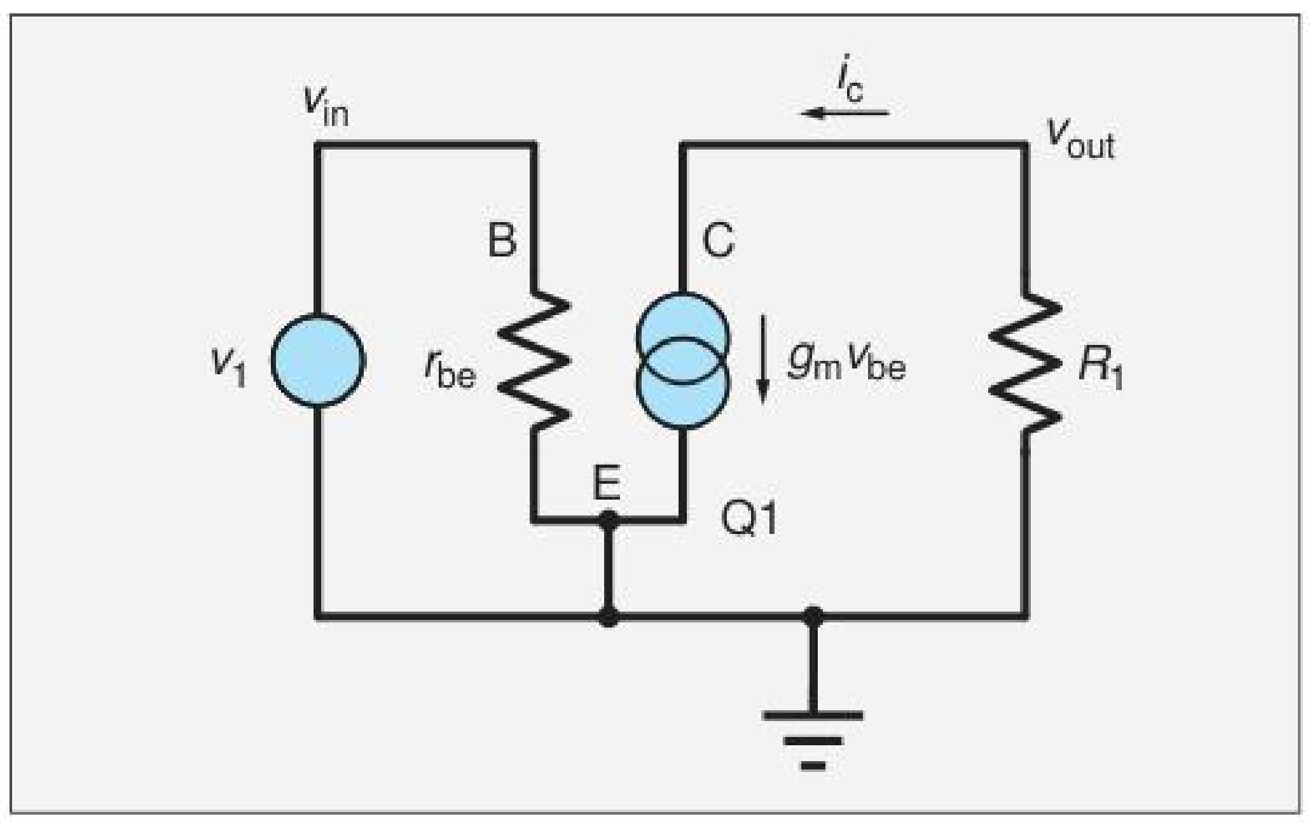


Fig.10. Small-signal model of circuit in Fig.9, redrawn with simplified layout.

Small-signal models

Fig.8 shows the small signal model of a transistor that we discussed last month. Fig.9 shows this model plugged into the circuit in Fig.7 in place of the transistor. We also note that we are only dealing with AC signals, so the power supply voltage is set to zero. A zero-volts voltage source is the same as a short circuit, so we can replace the supply (v_2 in Fig.9) with a short circuit. This is done for all DC power supplies in small-signal models. Similarly, the 0.635V DC bias voltage is not included, so the input source voltage (v_1 in the model) just produces the 5mV sinewave part of input. The effect of the bias is accounted for in the specific values used for model parameters such as r_{be} and g_m, where these vary with collector current operating point.

After replacing v_2 with a short we can redraw Fig.9 into the more compact and convenient form shown in Fig.10. We also generalise v_1 to be a signal source producing v_{in}, rather than the specific level of 5mV. From Fig.10 we can find, using Ohm's law, that $v_{out} = i_c R_1 = g_m v_{be} R_1$. Also $v_{be} = v_{in}$, so $v_{out} = g_m R_1 v_{in}$. This gives us the voltage gain of the circuit as $v_{out}/v_{in} = g_m R_1$. We discussed g_m (transconductance) last month and noted that $g_m = I_C/V_T$ for an operating current of I_C. So, substituting for g_m gives the gain as $-I_C R_1/V_T$ – the same result as discussed above).

We can also investigate the circuit using simulation. Fig.11 shows the results of an LTspice simulation of the circuit in Fig.7. Using a 5mV peak sinewave input, the output signal is centred on just over 6V and has an amplitude of about 1V. So the gain is around 200 – similar to the value indicated by the preceding calculations. Visually, the signal looks like an undistorted sinewave. If we increase the amplitude to 22mV we obtain the output shown in Fig.12 – here we can see distortion of sinewave due to the non-linear nature of the input-output relationship of this circuit (the positive peaks are wider than the negative peaks).

Bias Circuit

The circuit in Fig.4 achieves voltage amplification but it is not a practical implementation. In order for the circuit to work the input signal must have exactly the right DC offset to provide the bias voltage for the transistor – real-world

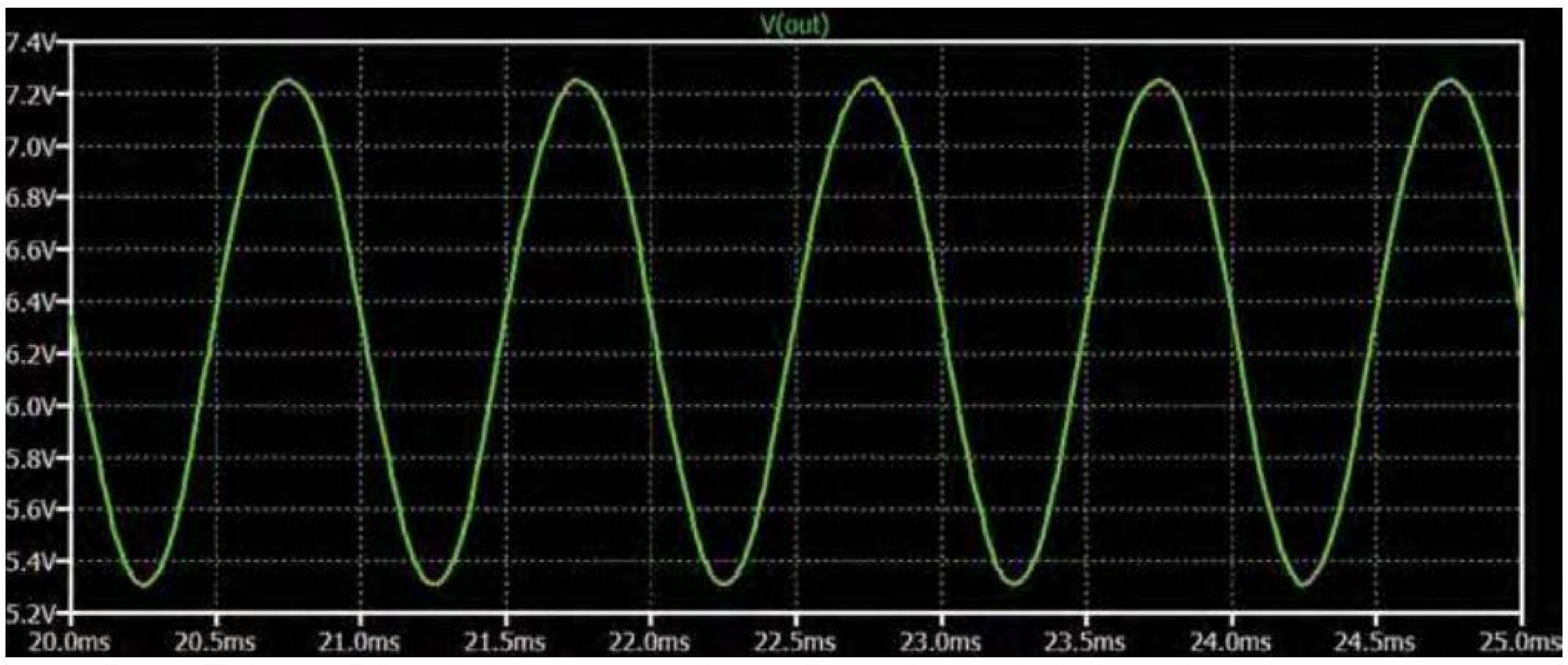


Fig.11. Simulated output from the circuit in Fig.7 (5mV peak input).

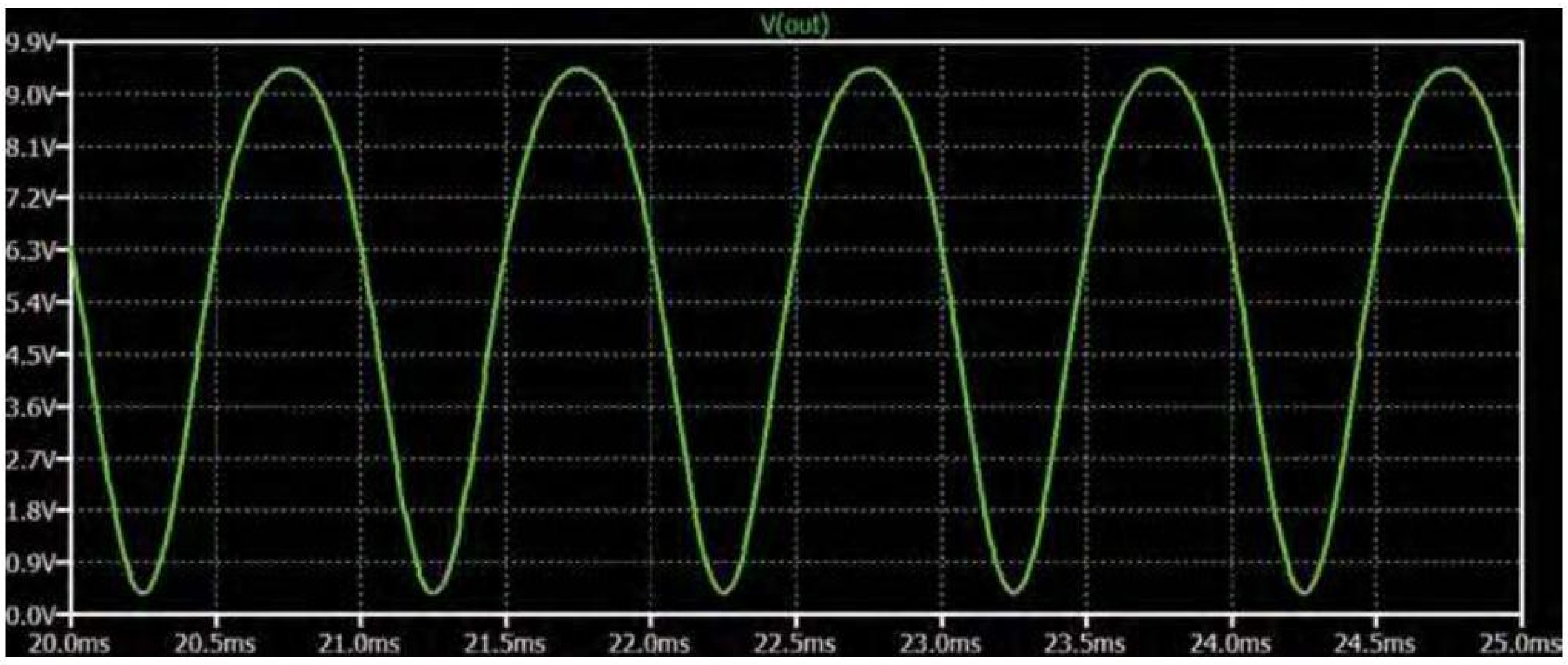


Fig.12. Simulated output from the circuit in Fig.7 (22mV peak input). Note the distortion of the sinewave.

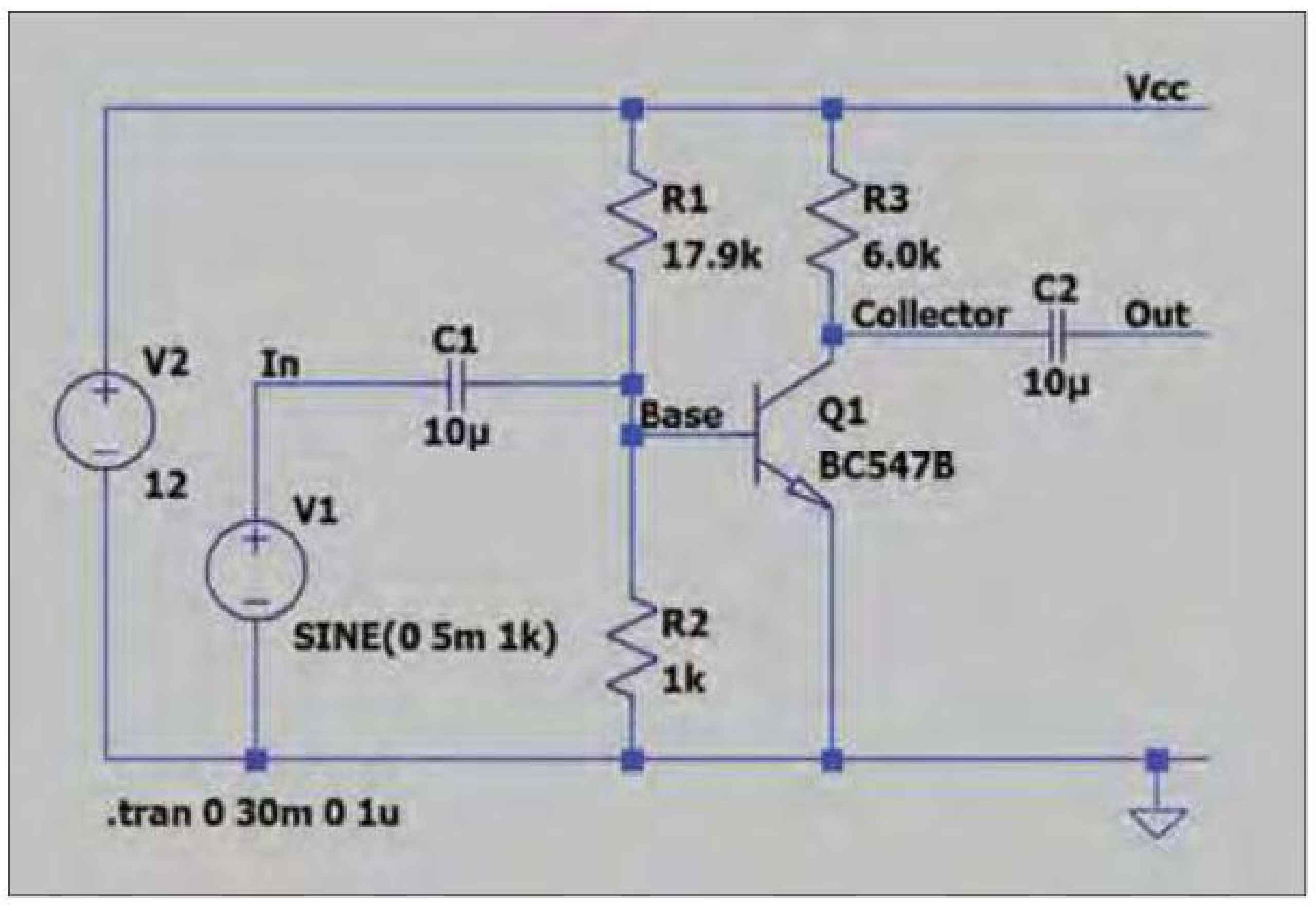


Fig.13. (left) Common-emitter amplifier with bias potential divider.

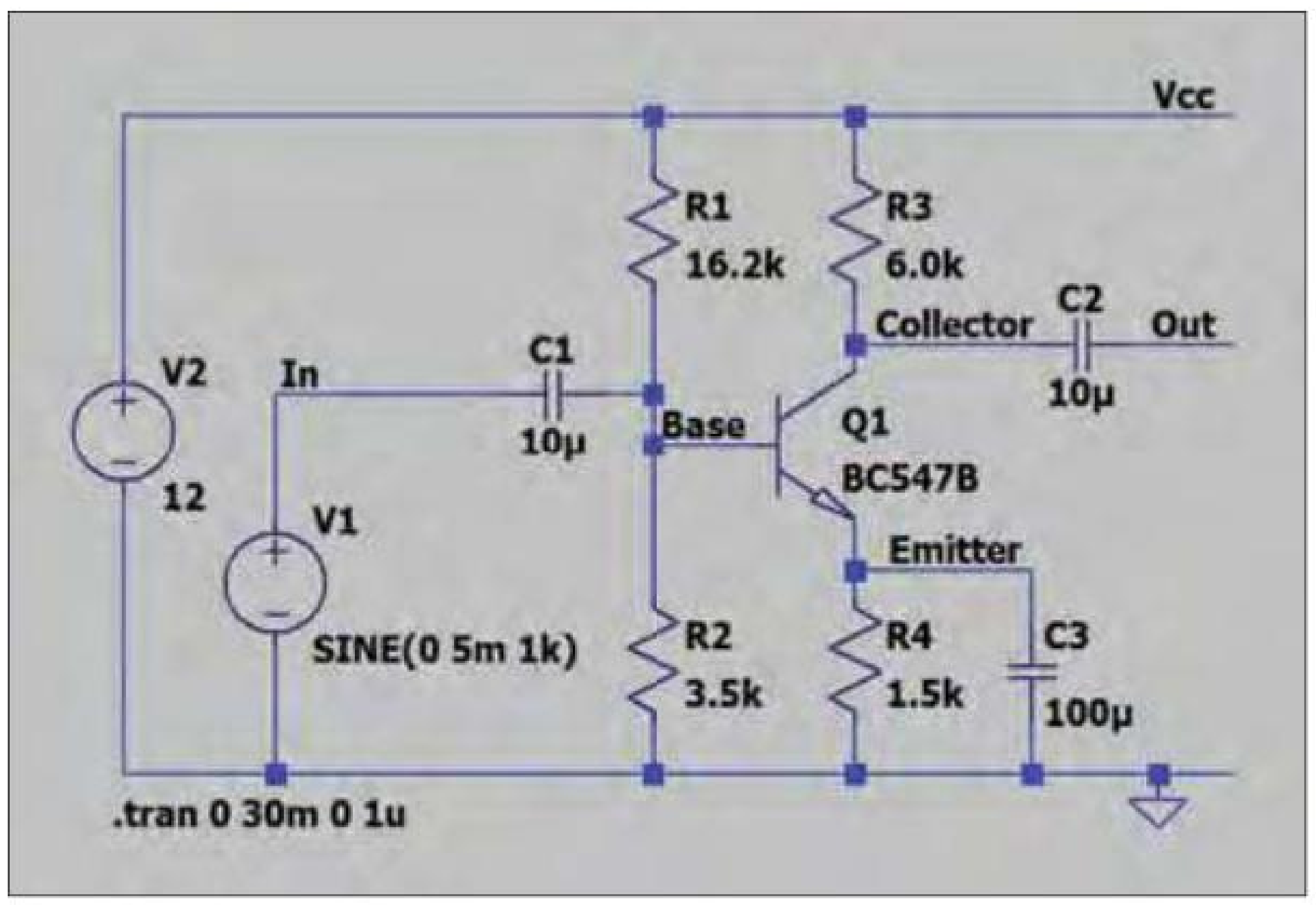


Fig.15. (right) Common-emitter amplifier with stabilised bias.

external signals are simply not that obliging. Typically, an AC signal will be centred on 0V or have an unknown and variable DC level. We can deal with this uncertainly using a coupling capacitor to block any DC from the input, but we have to provide the bias as part of our circuit design. This is actually straightforward to do in combination with a coupling capacitor for the input. We use a potential divider to set the base to the required bias voltage, as shown in Fig.13. The bias voltage is found using the potential divider formula:

$$V_{BIAS} = \frac{R_2}{R_1 + R_2} V_{CC}$$

We have V_{CC} = 12V and V_{BIAS} = 0.635V for our example. From this we can choose an infinite number of possible resistor values, so how do we choose? If the resistor values are too then low the circuit will consume more power than necessary, dissipated in the resistors. If the resistors are too large then the potential divider will not provide a 'stiff' enough voltage – variations in base current will shift the bias too much.

Knowing the required operating point of I_C = 1mA and assuming a rule of thumb current gain of 100, we might assume a base current of around 1mA/100 = 10µA. Another rule of thumb is that a potential divider should carry at least ten times the current that will be taken from it. So for this case we need at least 100µA, which corresponds to a maximum total resistance ($R_1 + R_2$) across 12V of 12V/100µA = 120kΩ. If we choose R_2 = 1kΩ we get R_1 = 17.9kΩ, and a total resistance that is well below the maximum but does not significantly increase the circuit's supply current. The results of simulating the circuit in Fig.13 are shown in Fig.14 (base and collector signals). It can be seen that the collector signal is similar to that in Fig.11 and comparison of the two waveforms shows the inverting behaviour of the amplifier. The waveforms in Fig.14 are directly at the base and collector, the input and output waveforms on the other side of the coupling capacitor are centred on 0V.

Feedback

Unfortunately, we still do not really have a practical circuit implementation. The circuit in Fig.13 works fine in a single, correctly configured simulation. However, in practice, due to the exponential relationship between V_{BE} and I_C (as shown in Fig.3), only slight variation in V_{BE} from the designed value (for example due to individual transistors with different gains, or temperature changes) will result in large changes in the I_C operating point. To solve this problem we add a resistor connected to the emitter, as shown in Fig.15. This resistor provides negative feedback, which stabilises the bias.

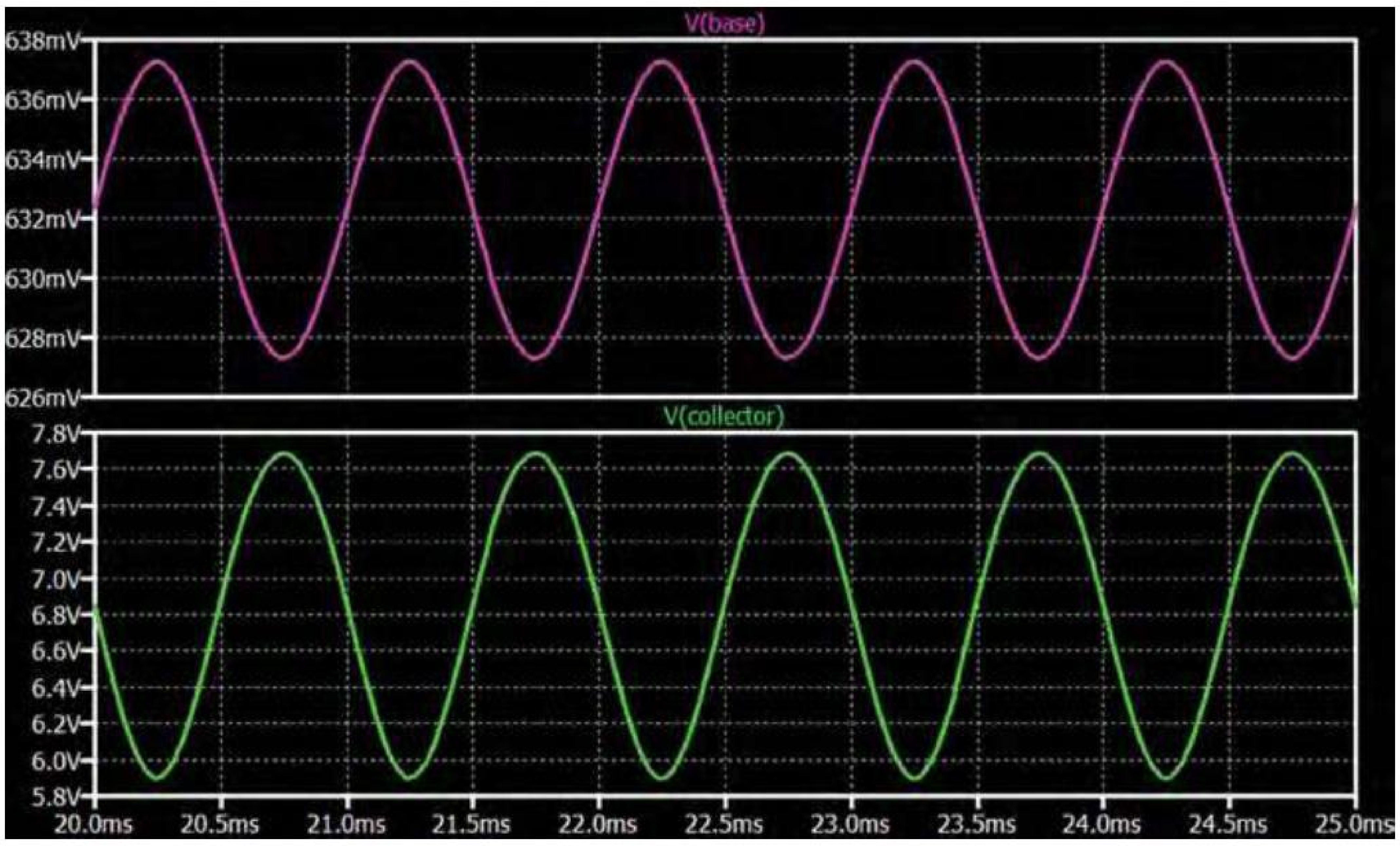


Fig.14. Simulation results for the circuit in Fig.13 (top `V1` input, bottom `Out` output).

To understand how the feedback works, first note that we have a voltage at the emitter of value $I_E R_4$, so the V_{BE} bias voltage is the difference between this and the potential divider voltage produced by R_1 and R_2. Assume that the potential divider provides a fixed voltage at the base – however, the emitter voltage can vary. Consider an increase in emitter current, for example due to a change in temperature of the transistor. This will increase the voltage drop across R_4, resulting in a smaller V_{BE}, which will tend to reduce the emitter current. This is the negative feedback in action – changes in emitter current result in changes in V_{BE} that tend to oppose the change in emitter current. This has the effect of stabilising the operating point of the transistor. The feedback will apply to the signal too, greatly reducing the gain, We may want this, but if not we can bypass the emitter resistor with a capacitor, as shown in Fig.15, so that the feedback only applies to DC or very low frequency signals.

To find the resistor values for the circuit in Fig.15 we can proceed as follows. Choose the operating point collector current (we will stay with 1.0mA). Choose the no-signal collector voltage and set the collector resistor accordingly (R_3 as before). Choose the emitter voltage, this is fairly arbitrary – higher values will give more feedback, but reduce the available output amplitude. Base voltages up to about a third of the supply are typical (with the emitter V_{BE} below this). We will use 1.5V, requiring R_4 = 1.5kΩ with the 1mA operating current. Select the base potential divider to give the required base voltage relative to the emitter. We stay with V_{BE} = 0.635V , so we need 2.135V (1.5 + 0.635) from the potential divider, selecting 3.5kΩ and 16.2kΩ to achieve this with a similar total resistance to the previous circuit.

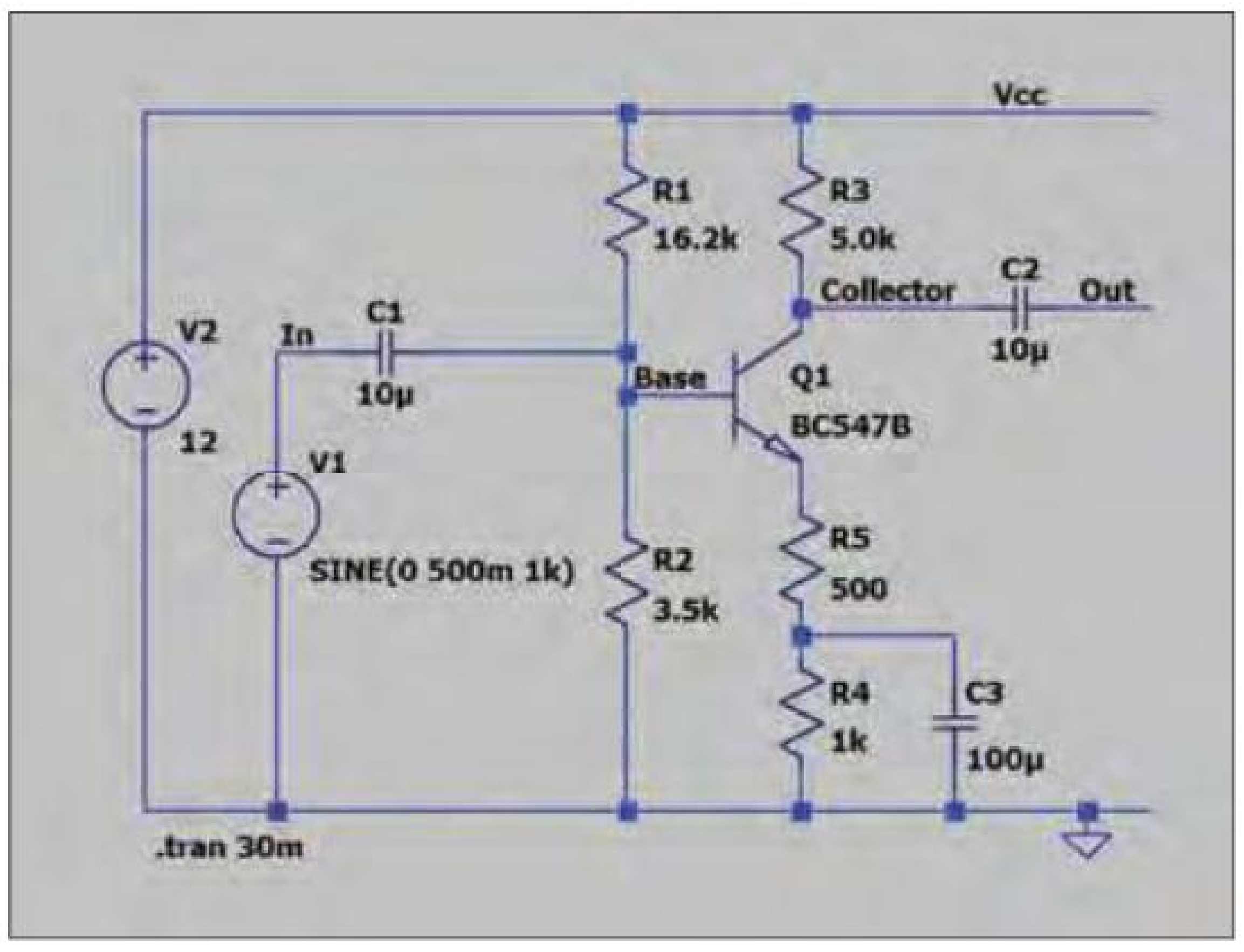


Fig.16. Common-emitter amplifier with stabilised bias and AC feedback.

Setting gain

As noted, the emitter resistor bypass capacitor in the circuit in Fig.15 prevents the feedback from affecting the AC signal. The gain of the circuit is around 200, like our other examples, but with the signal at the collector centred closer to the designed value of 6V. However, the circuit still suffers from distortion (as shown in Fig.12) when outputting relatively large amplitudes, although maximum amplitude is reduced due to the voltage dropped across R_E. There are a couple of issues here. First, the distortion is undesirable; and second, we cannot set the gain to the value we want. Applying feedback to the signal as well as the bias can help us with both these points. Negative feedback makes circuits gain depend on the feedback network components, not on the amplifier itself, as long as the gain of the amplifier is significantly larger than the gain with feedback. This is well known for op amp circuits, where two resistors are used to set the gain. The reduction of dependence of the circuit on the amplifier reduces the effect of amplifier nonlinearities, so applying negative feedback reduces distortion.

Without the bypass capacitor (C_3) the amplifier in Fig.15 has a gain of $-R_3/R_4$ as long as this value is much less than the gain without feedback. The choice of R_3 and R_4 to set bias and gain may conflict, but this can be avoided by bypassing only part of the total emitter resistance. A design example is shown in Fig.16. Here, the bias is the same as in the circuit in Fig.15 (1.5kΩ total emitter resistance). The gain of the circuit is related to the part of the emitter resistance that is not bypassed, specifically it is $-R_3/R_5$ which is 10 (5000/500) with the values shown. The value of R_3 was changed to allow a larger output amplitude (about 5V peak) centred on 7V. This has a similar amplitude to the signal shown in Fig.12, but with much less distortion (see Fig.17).

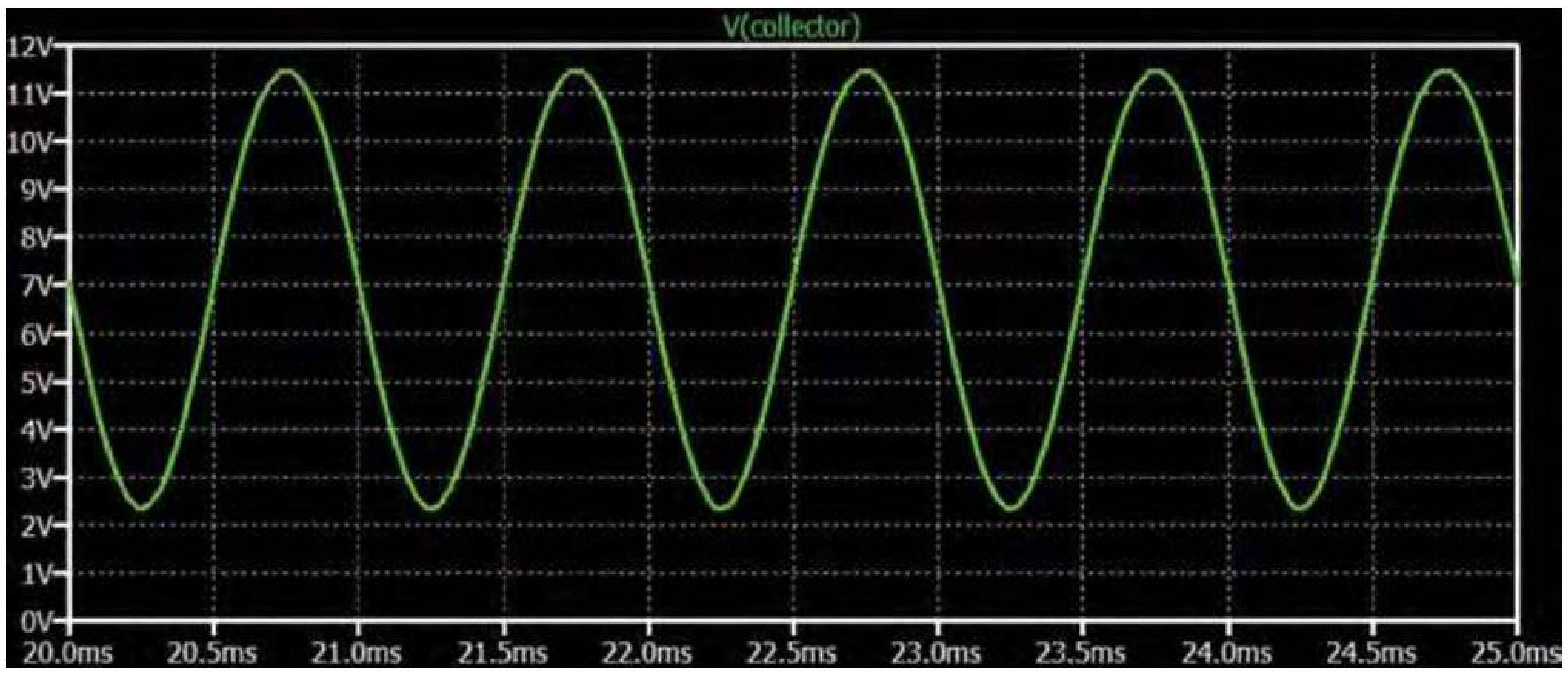


Fig.17. Simulated output from the circuit in Fig.16 (500mV peak input).

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AUDIO OUT

By Jake Rothman

The PE Theremin – Part 3

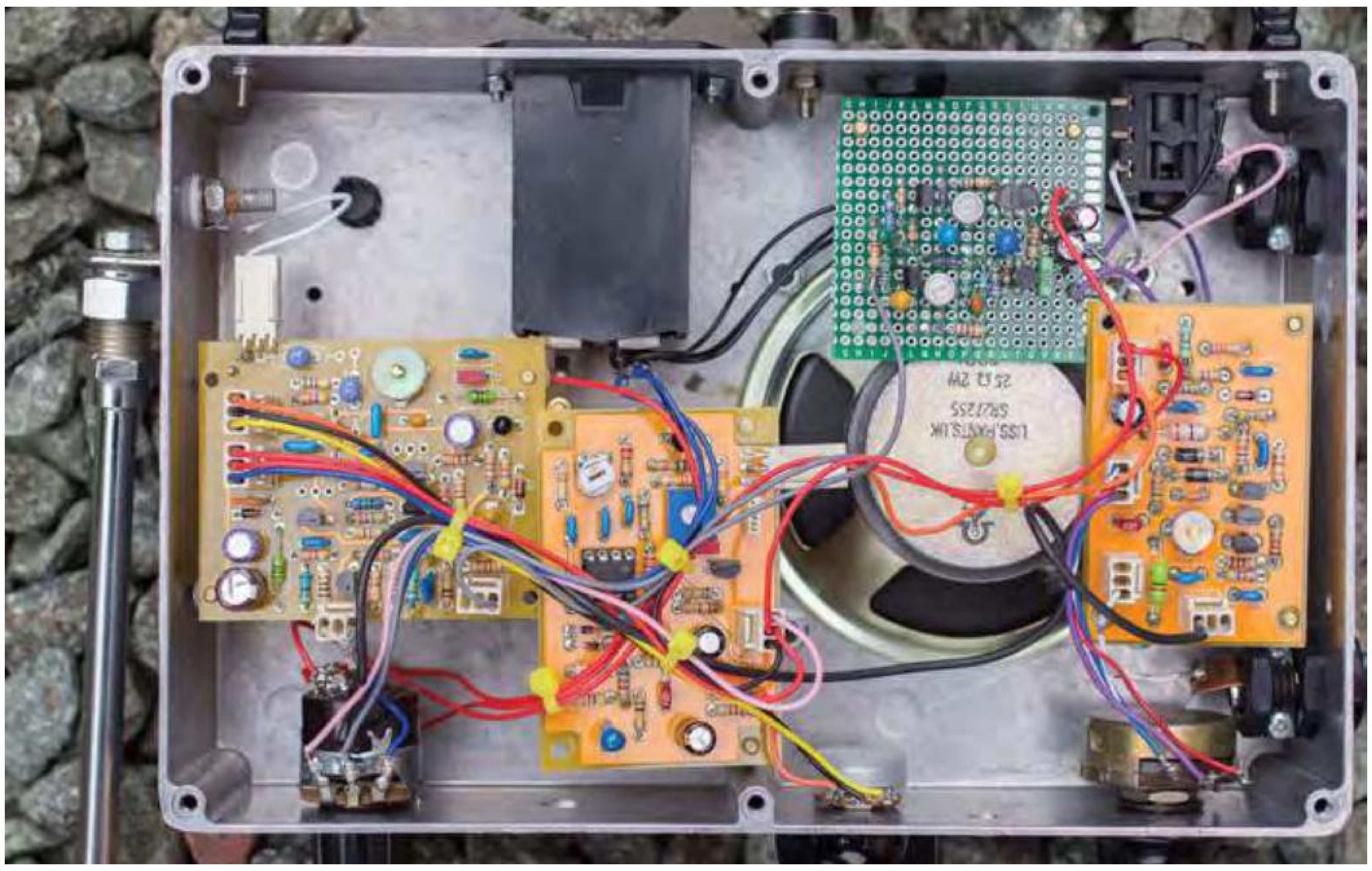


Fig.20. Theremin built into a die-cast metal case. (Photo: Harvey Rothman)

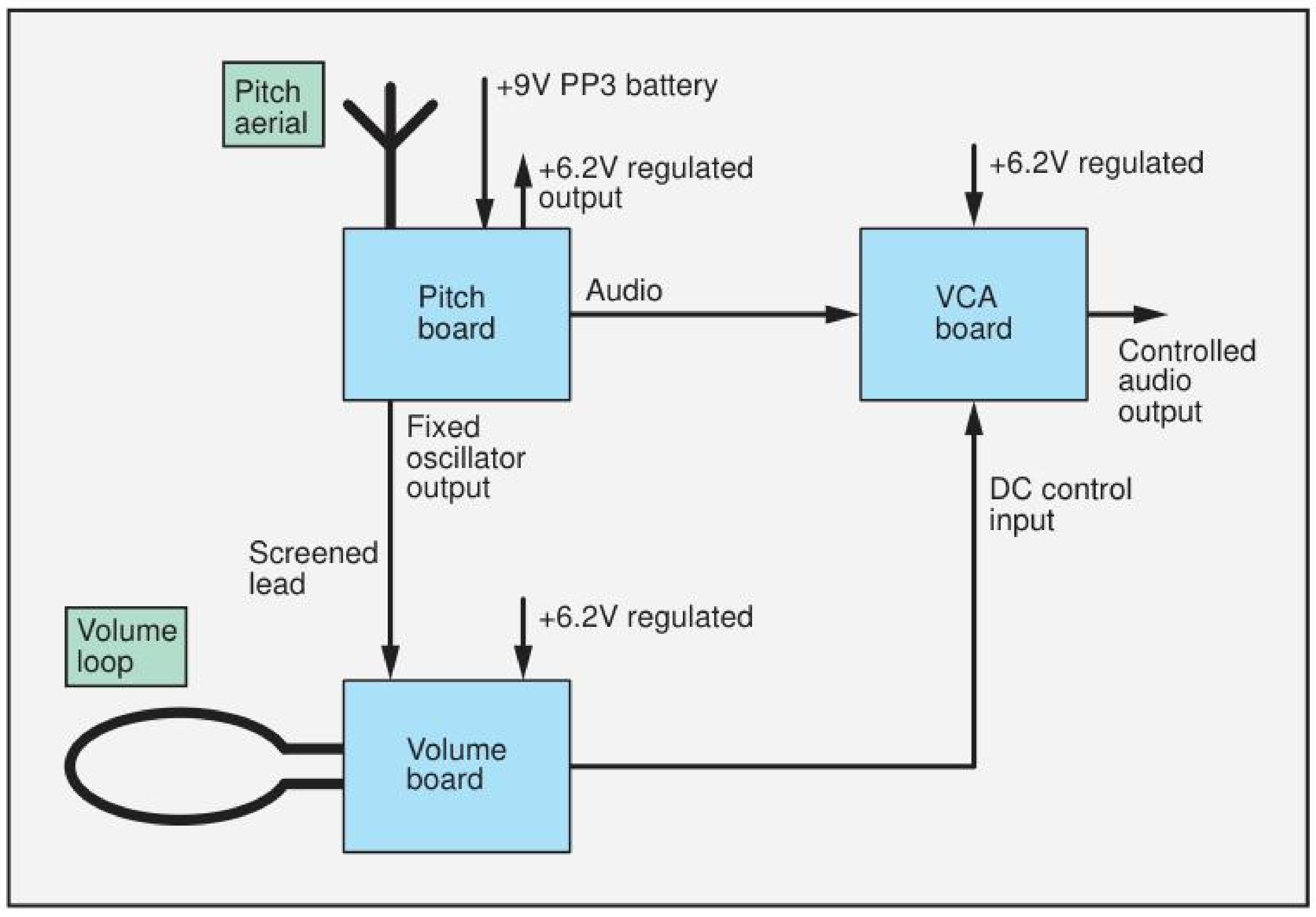
Last month, we built the main PE Theremin section – the pitch control board. Next, we'll look at all the other components to make a complete instrument, housed in a metal case, as shown on the first page of *Part 1* and above in Fig.20 for the internal arrangement. All my circuits are designed for minimal power consumption – here I've achieved a total current consumption of only 8mA, which I hope will lead to a future low-cost battery-powered instrument. A 6.2V Zener regulator is provided on the pitch board, which is used to feed the volume and VCA boards. (If the pitch board is used on it's own, the Zener resistor R1 can be increased to 820Ω.)

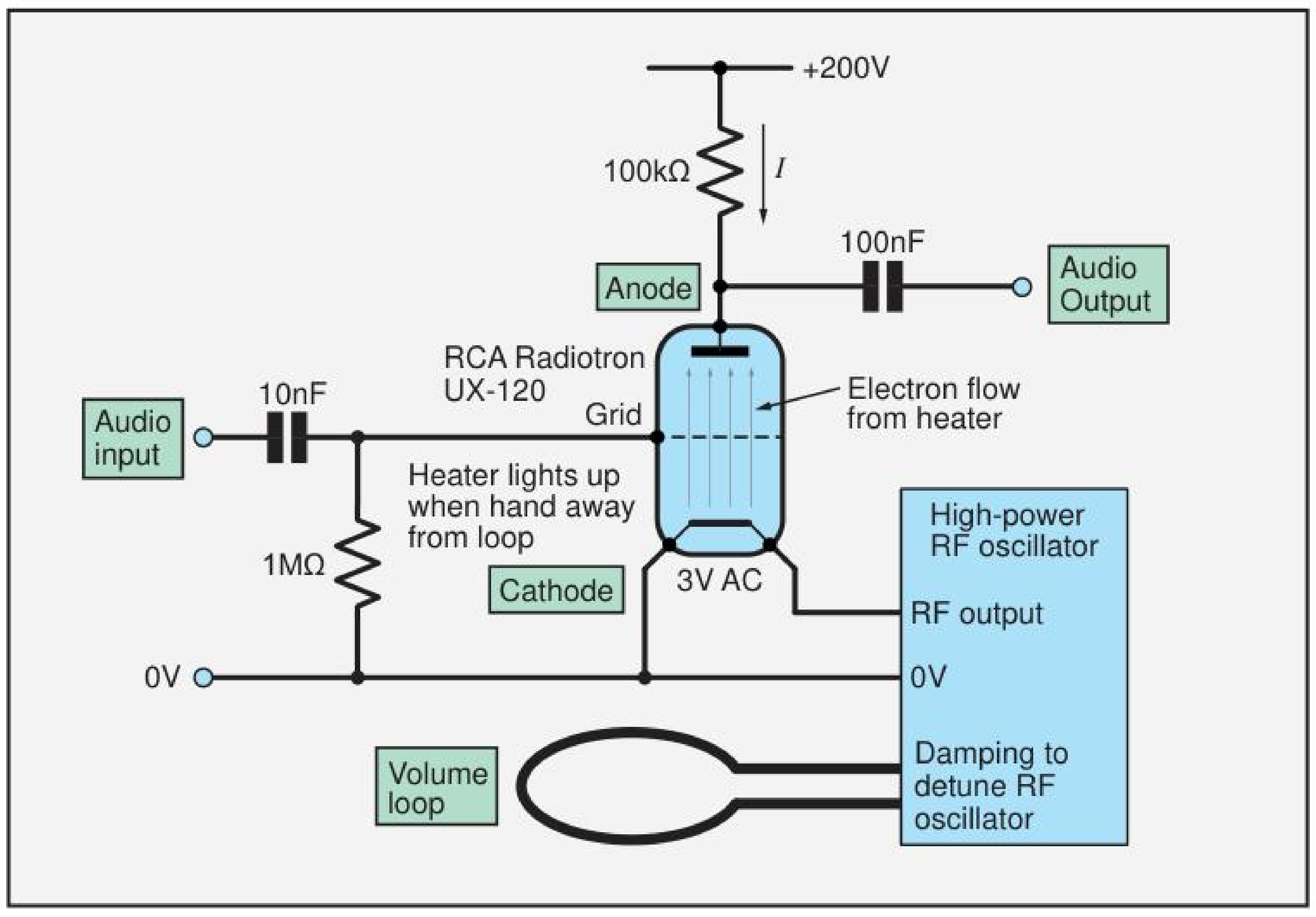
System PCB design

To minimise production costs, I normally design complete Theremins on one PCB. For home constructors it is advantageous to split the design into three sections, as shown in Fig.21 (pitch, VCA and volume – plus amplifier and PSU). One reason is that human arms are about 18 inches (450mm) apart, so this dictates the optimum aerial spacing. It is a good idea to minimise the wire length from board to aerial. It then makes sense to have a separate dedicated RF PCB next to each aerial. The buffered fixed oscillator output is sent down a length of coaxial cable to drive the volume circuit. The VCA audio board is best placed in the middle to avoid RF contamination. The power amplifier to drive the speaker is subject to variations in the power the user requires. Some will want just 250mW, others will want 50W for concert use, but a line output jack to feed a guitar amp will do for most. The power supply will depend on the amplifier power needed. Finally, being involved in education, the PCB size is limited to 80mm square on the student (free) edition of Eagle CAD.

Volume control

It's one thing to be able to play pitch, but to play proper tunes there has to be a way to control volume as well. This part of the Theremin is usually more complicated than the pitch section. There are lots of different approaches to the problem. Leon Theremin's unique technique was


Pitch aerial
+9V PP3 battery
+6.2V regulated output
+6.2V regulated
Pitch board
Audio
VCA board
Controlled audio output
Fixed oscillator output
DC control input
Screened lead
Volume loop
+6.2V regulated
Volume board
Fig.21. Block diagram of the PCB modules for the complete Theremin – the power amplifier and PSU are additional modules.


+200V
100kΩ
I
100nF
Anode
Audio Output
RCA Radiotron UX-120
10nF
Grid
Electron flow from heater
Audio input
Heater lights up when hand away from loop
1MΩ
Cathode
3V AC
High-power RF oscillator
RF output
0V
0V
Volume loop
Damping to detune RF oscillator
Fig.22. Leon Theremin's unique valve VCA – the hotter the heater the louder the volume.

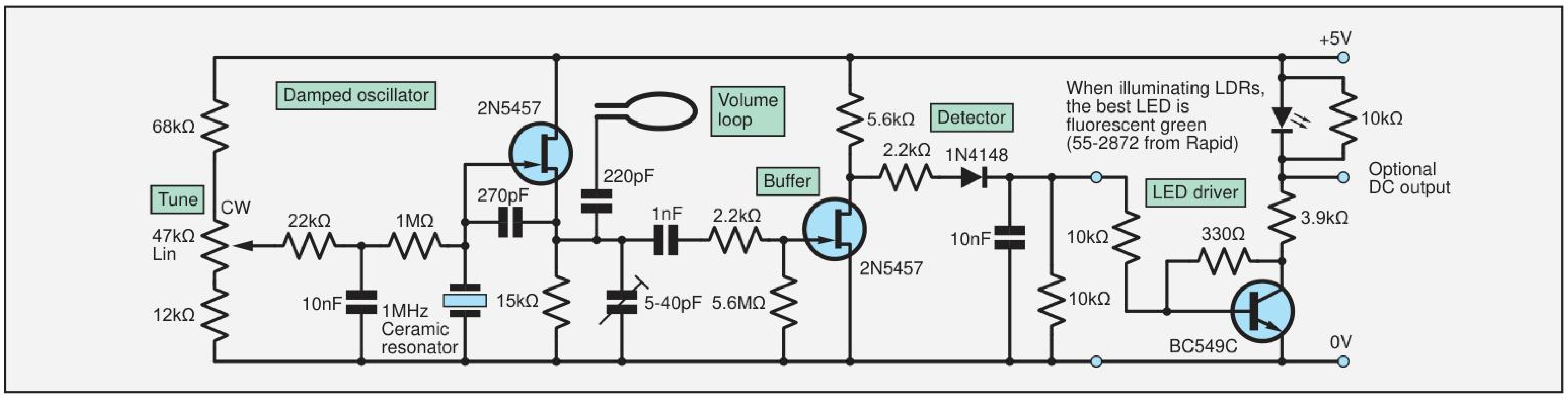

+5V
Damped oscillator
2N5457
Volume loop
5.6kΩ
Detector
When illuminating LDRs, the best LED is fluorescent green (55-2872 from Rapid)
10kΩ
68kΩ
2.2kΩ
1N4148
Tune
CW
220pF
Buffer
LED driver
Optional DC output
270pF
3.9kΩ
22kΩ
1MΩ
1nF
2.2kΩ
47kΩ Lin
10nF
10kΩ
330Ω
2N5457
10nF
1MHz Ceramic resonator
15kΩ
5-40pF
5.6MΩ
10kΩ
12kΩ
BC549C
0V

Fig.23. Damped RF oscillator produces a control voltage to drive an LED shining on an LDR to give volume control.

a voltage-controlled amplifier (VCA) employing a directly heated thoriated tungsten filament triode; the heater temperature was varied to control electron emission and hence the gain (Fig.22).

Early (1930s) production RCA Theremins used a Radiotron UX-120 valve, an audio output valve designed for battery-powered radios. The heater voltage was supplied from a radio frequency oscillator where the hand capacity could be used to damp it, resulting in a low output. When the hand was taken away, the output peaked and the heater went to full brightness. This led to the negative play response that characterises the original 'classical' Theremins, where the volume goes down as the hand is brought closer.

The damped oscillator technique, similar to the radio ham's grid-dip oscillator, is still in common use today, except now the RF output is detected by a rectifier, smoothed and fed into a VCA or FET. It might be possible to emulate the original theremin idea and feed RF directly into an LED shining onto an LDR (light-dependent resistor). The circuit in Fig.23 is one I use for my cheap Theremins. It has been made into a small add-on box (Fig.24) to use with pitch-only Theremins.

Another approach is to use a second Theremin and then do a frequency-to-voltage conversion, before feeding it into a VCA, as shown in Fig.25. This is what I have found gives the widest smoothest control, and I used this in my more expensive *Elysian Theremin* design (Fig.26) in the November/December 1996 issues of *EPE*. We'll revisit this design when I've redone the PCB to incorporate 20 years of improvements.

Spurious whistles

A common problem with Theremin volume circuits is that its oscillators can interfere with those of the pitch circuit, resulting in low-level whistles as harmonics present from all the oscillators beat together. To avoid this, the frequencies of the two Theremin circuits (four oscillators) of the *Elysian Theremin* were chosen so that no harmonics lay within audio frequencies of each other.

Another problem is hand movements of the volume plate also affecting the pitch. This interaction effect is exhibited by all Theremins to some extent, especially if the volume loop is

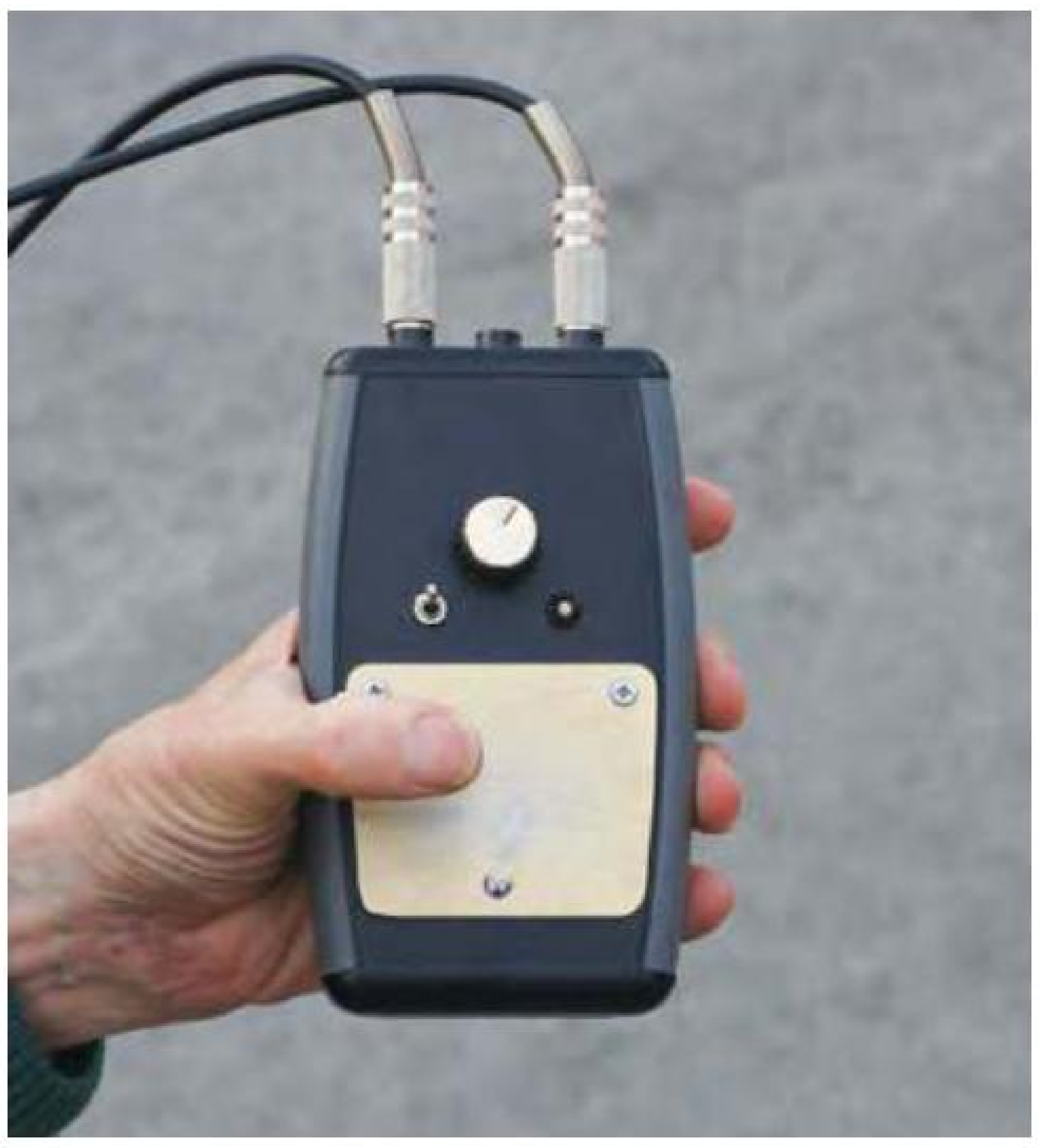


Fig.24. Self-contained volume control box based on the circuit in Fig.23.

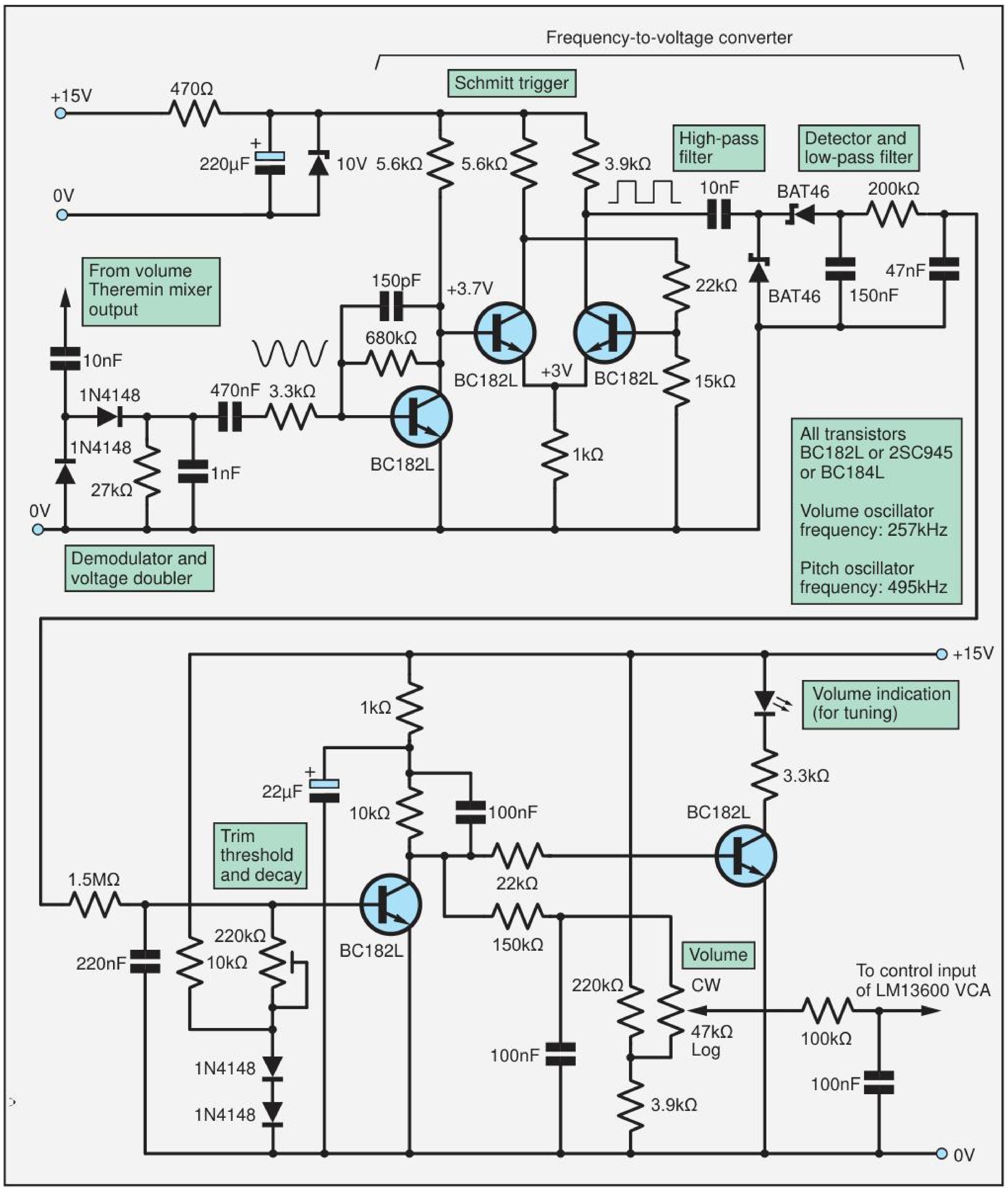

Frequency-to-voltage converter
Schmitt trigger
+15V
470Ω
High-pass filter
Detector and low-pass filter
220µF
10V
5.6kΩ
5.6kΩ
3.9kΩ
0V
10nF
BAT46
200kΩ
From volume Theremin mixer output
150pF
+3.7V
22kΩ
47nF
BAT46
150nF
680kΩ
10nF
+3V
BC182L
BC182L
15kΩ
1N4148
470nF
3.3kΩ
1N4148
1kΩ
1nF
27kΩ
BC182L
All transistors BC182L or 2SC945 or BC184L
Volume oscillator frequency: 257kHz
Pitch oscillator frequency: 495kHz
0V
Demodulator and voltage doubler
+15V
1kΩ
Volume indication (for tuning)
3.3kΩ
22µF
10kΩ
100nF
BC182L
Trim threshold and decay
1.5MΩ
22kΩ
220kΩ
150kΩ
220nF
10kΩ
BC182L
Volume
220kΩ
CW
To control input of LM13600 VCA
47kΩ Log
100kΩ
100nF
1N4148
100nF
1N4148
3.9kΩ
0V

Fig.25. The volume control system of the *Elysian Theremin*. The output of the volume plate Theremin is fed into a frequency-to-voltage converter based on a Schmitt trigger, filter and rectifier. The resulting control voltage is then fed into a transconductance VCA.

Fig.26. The *Elysian Theremin*; a complex but smooth performer.

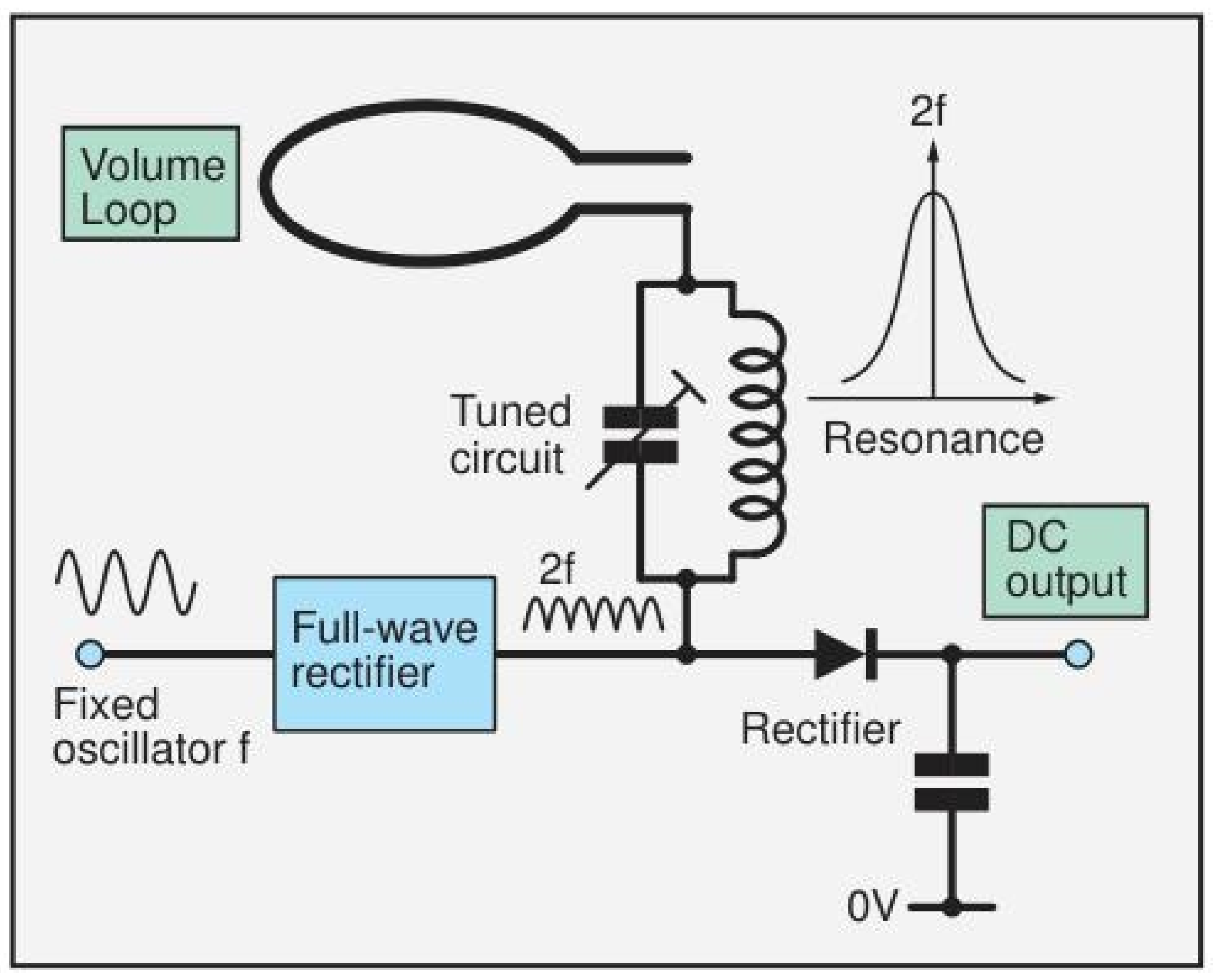

Volume Loop
2f
Tuned circuit
Resonance
DC output
2f
Full-wave rectifier
Fixed oscillator f
Rectifier
0V

Fig.27. Henk frequency doubler system.

touched. There is a solution devised by Theremin engineer Tony Henk in 1995, where the volume loop high-frequency drive signal is derived from the fixed oscillator in the pitch Theremin. The trick is to put this through a frequency doubler. The doubled cycles on the volume loop then result in no net charge being transferred via the hands to the pitch aerial, keeping the pitch control stable. Also, because there are no extra oscillators, the spurious whistle problem is avoided as well. The system's block diagram is shown in Fig.27.

The simplest frequency doubler is a full-wave rectifier. Every engineer knows that the output ripple is double the input frequency. Normally, op amps and diodes are used, which can be slow for RF use. Luckily, I came across a simple circuit by Peter Baxandall in the March 1973 issue of *Wireless World*, which only used two transistors. By placing a tuned circuit into the collector load rather than a resistor, I had a working volume loop circuit, which could be detuned by hand capacity effects. The resulting design is shown in Fig.28, with the necessary input and output buffers. Note the 'input buffer' is the output buffer (TR4) on the pitch PCB. The cheapest buffer for RF applications is a FET source follower.

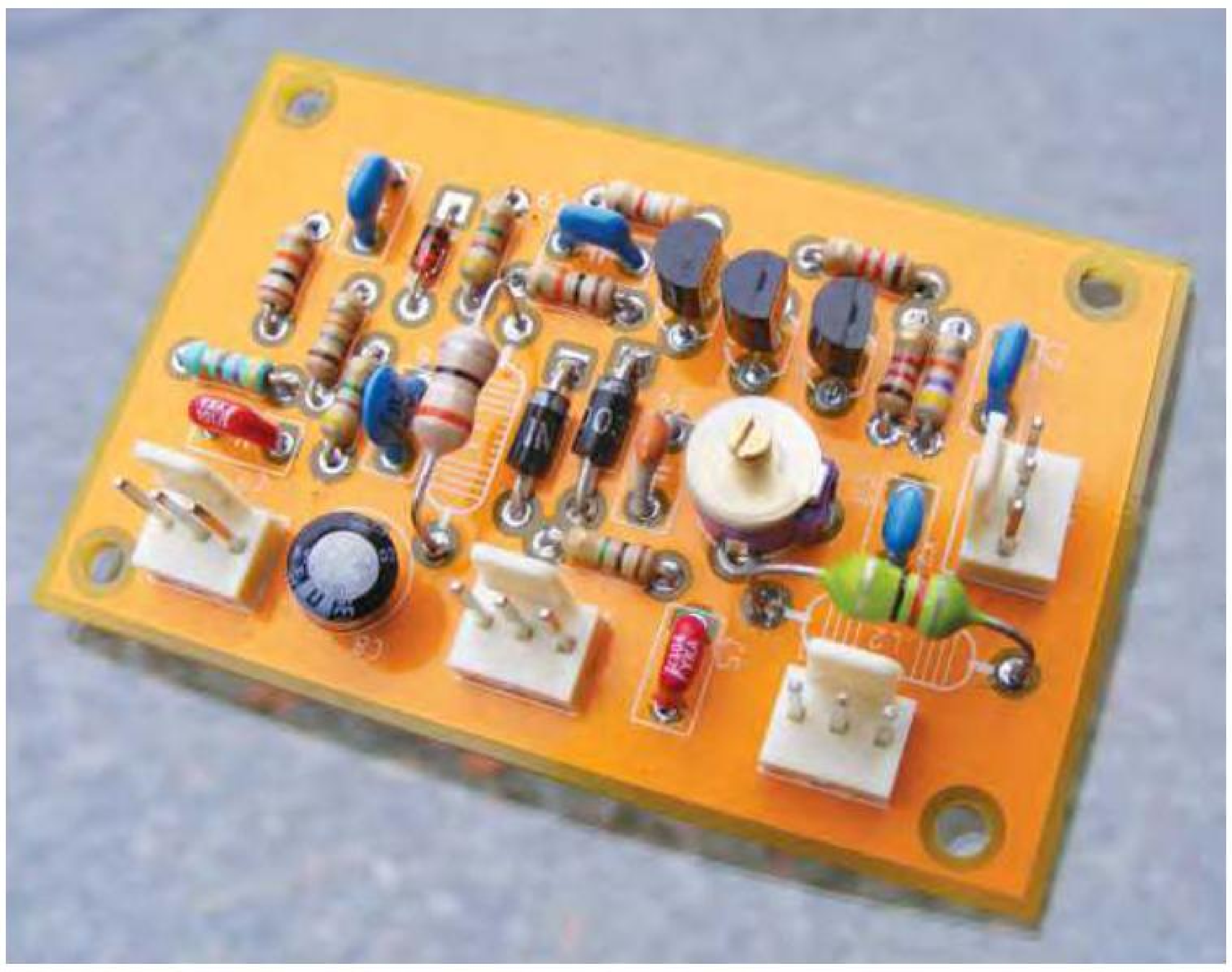


Fig.29. Completed Theremin volume loop PCB – constructors need to mount inductors 10mm above the copper ground plane to prevent damping.

My first PCB for the volume plate circuit failed to work properly because of the Q damping effect of the groundplane (see Fig.29) until I mounted the inductors 10mm *above* the board. The layout for the PCB is shown in Fig.30. Note that the coax cable cannot normally be crimped into Molex connector pins unless the very thin Farnell cable specified below is used. It can, however, be soldered if you prefer.

Parts list for volume control PCB

Semiconductors

TR1, TR2 BC182, BC549 etc. NPN general purpose bipolar
TR3 BF244A or BF245A general purpose N-channel JFET centre gate pin-out
D1, D2 1N4003 old-fashioned rectifier or posh 30pF varicap diodes if obtainable
D3 1N4148

Resistors (*All 5% 0.25W carbon-film*)

R1, R3 1.2kΩ
R2 47kΩ
R4 1MΩ
R5, R6 4.7MΩ
R7 10kΩ
R8 3.9kΩ
R9 470Ω
R10 47kΩ
R11 33kΩ
VR1 47kΩ potentiometer (log)

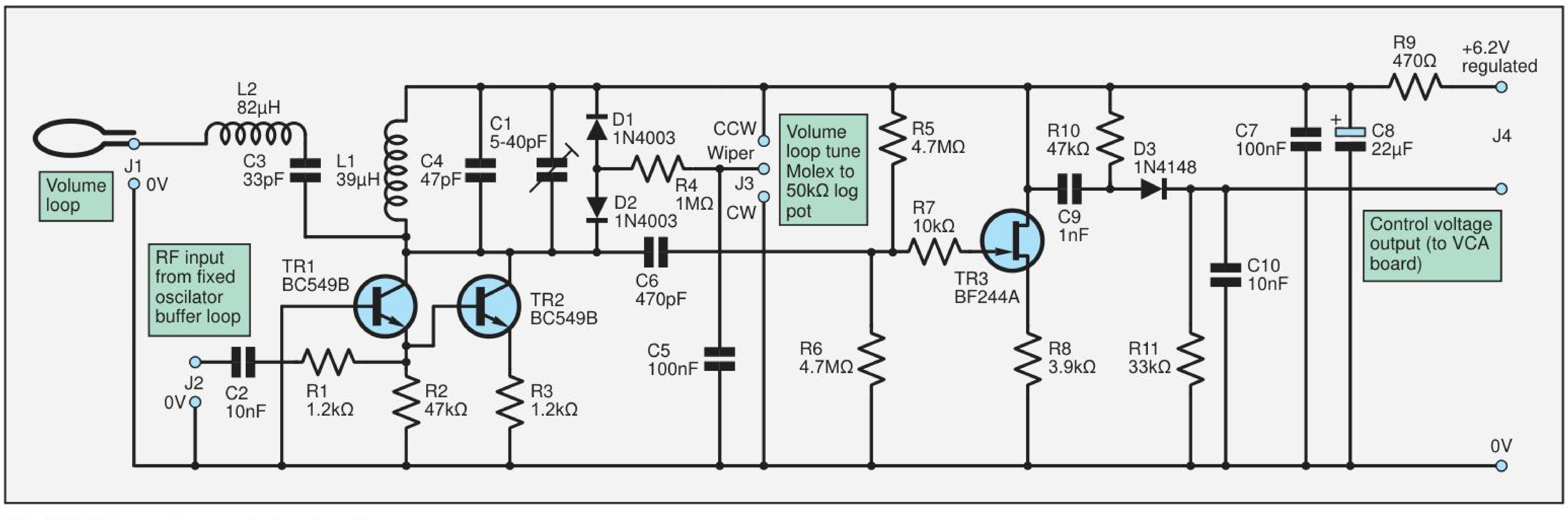

L2
82µH
J1
0V
Volume loop
C3
33pF
L1
39µH
C4
47pF
C1
5-40pF
D1
1N4003
CCW
Wiper
R4
1MΩ
J3
CW
D2
1N4003
Volume loop tune Molex to 50kΩ log pot
R5
4.7MΩ
R7
10kΩ
R10
47kΩ
D3
1N4148
C9
1nF
TR3
BF244A
C7
100nF
+
C8
22µF
R9
470Ω
+6.2V regulated
J4
Control voltage output (to VCA board)
C10
10nF
RF input from fixed oscilator buffer loop
TR1
BC549B
TR2
BC549B
C6
470pF
C5
100nF
R6
4.7MΩ
J2
0V
C2
10nF
R1
1.2kΩ
R2
47kΩ
R3
1.2kΩ
R8
3.9kΩ
R11
33kΩ
0V

Fig.28. The volume plate circuit.

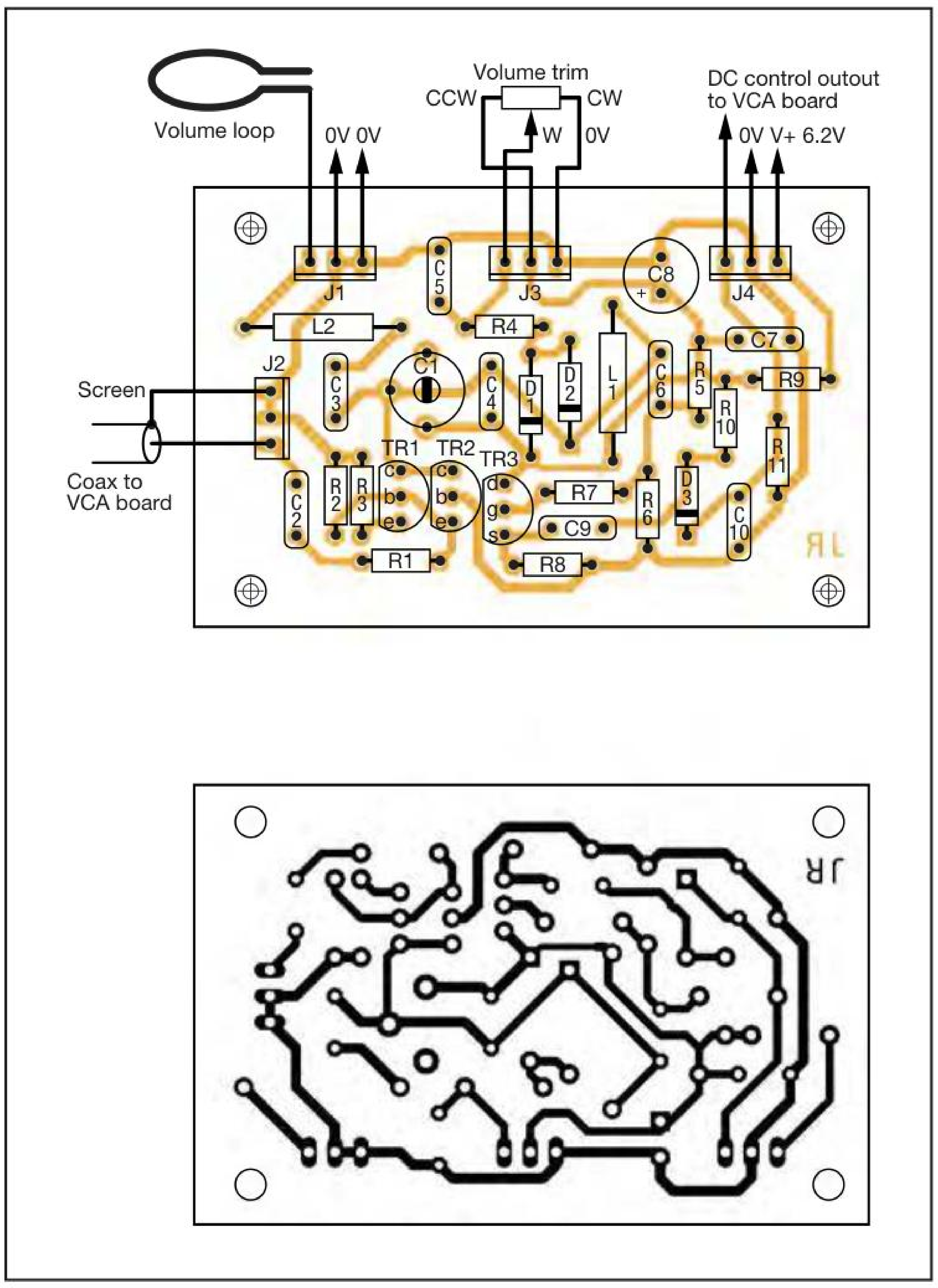

Volume loop
0V 0V
Volume trim
CCW
CW
W
0V
DC control outout to VCA board
0V V+ 6.2V
J1
J3
J4
C5
C8
L2
R4
C7
J2
Screen
C1
C3
C4
D1
D2
L1
C6
R5
R9
R10
R11
Coax to VCA board
TR1
TR2
TR3
C2
R2
R3
R7
R6
D3
C10
C9
R1
R8
JR

Fig.30. Volume plate PCB overlay.

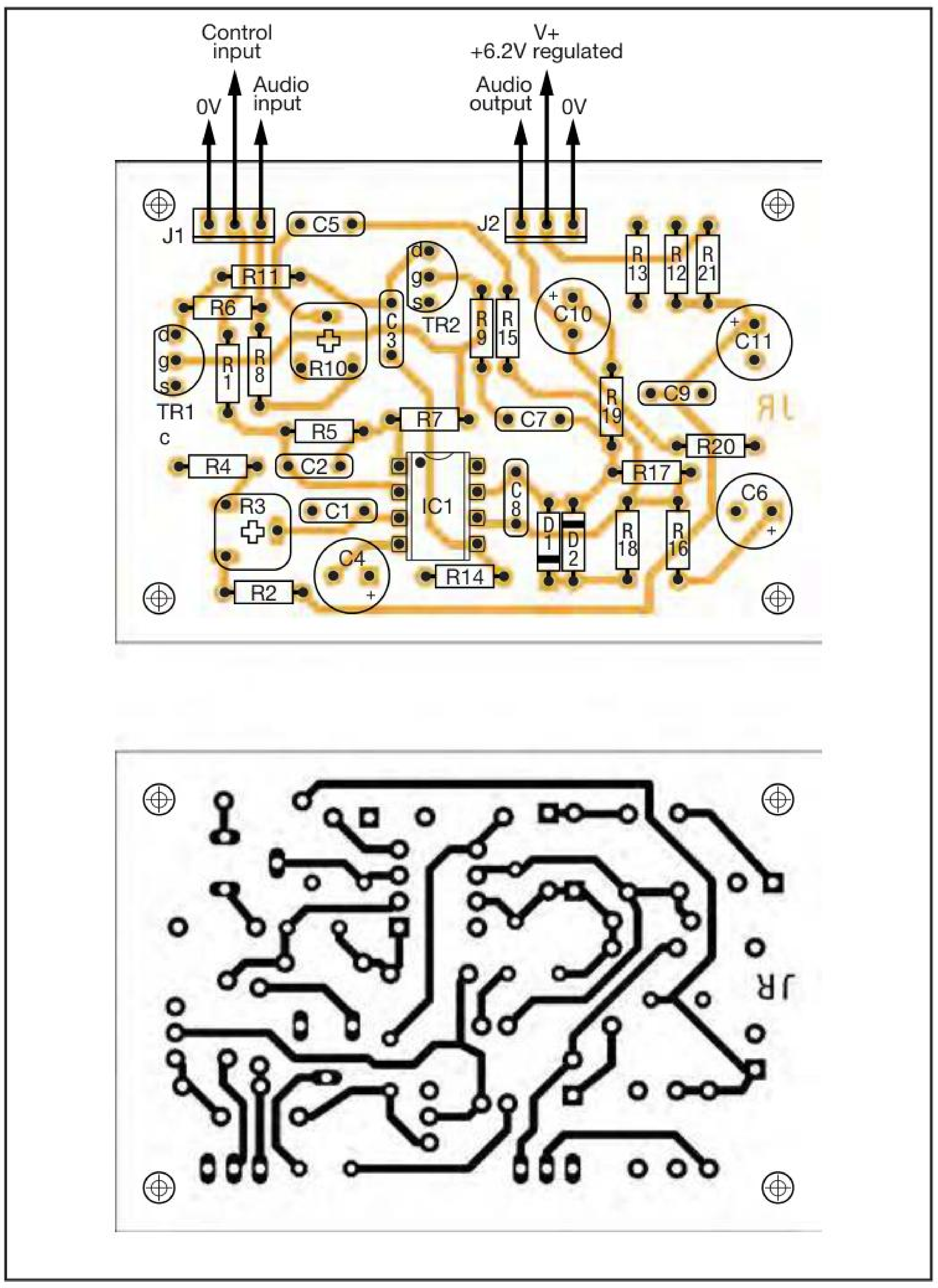

Control input
0V
Audio input
V+ +6.2V regulated
Audio output
0V
J1
C5
J2
R11
R13
R12
R21
R6
TR2
C10
C3
R9
R15
C11
TR1
R1
R8
R10
R19
C9
R5
R7
C7
R20
R4
C2
R17
C6
R3
C1
IC1
C8
D1
D2
R18
R16
C4
R14
R2
JR

Fig.32. JFET VCA PCB layout.

Capacitors (*All 5mm/0.2 inch spacing*)
C1 3-40pF plastic-film trimmer 7.5mm (Mullard 808 series, see Part 1)
C2, C9 10n X7R ceramic
C3 68pF NP0 ceramic
C4 39pF NP0 ceramic
C5, C7 100nF X7R ceramic
C6 470pF X7R ceramic
C8 22µF 6.3V or 10Velectrolytic or tantalum

Inductors
L1 39µH axial Bourns 78F390J-RC Mouser
L2 82µH axial Bourns 78F820J-RC Mouser

Miscellaneous
RF coax 480mm/20 inches long, type not critical; eg RG178PE Farnell 149-071
Molex connectors 3-pin, 4 off

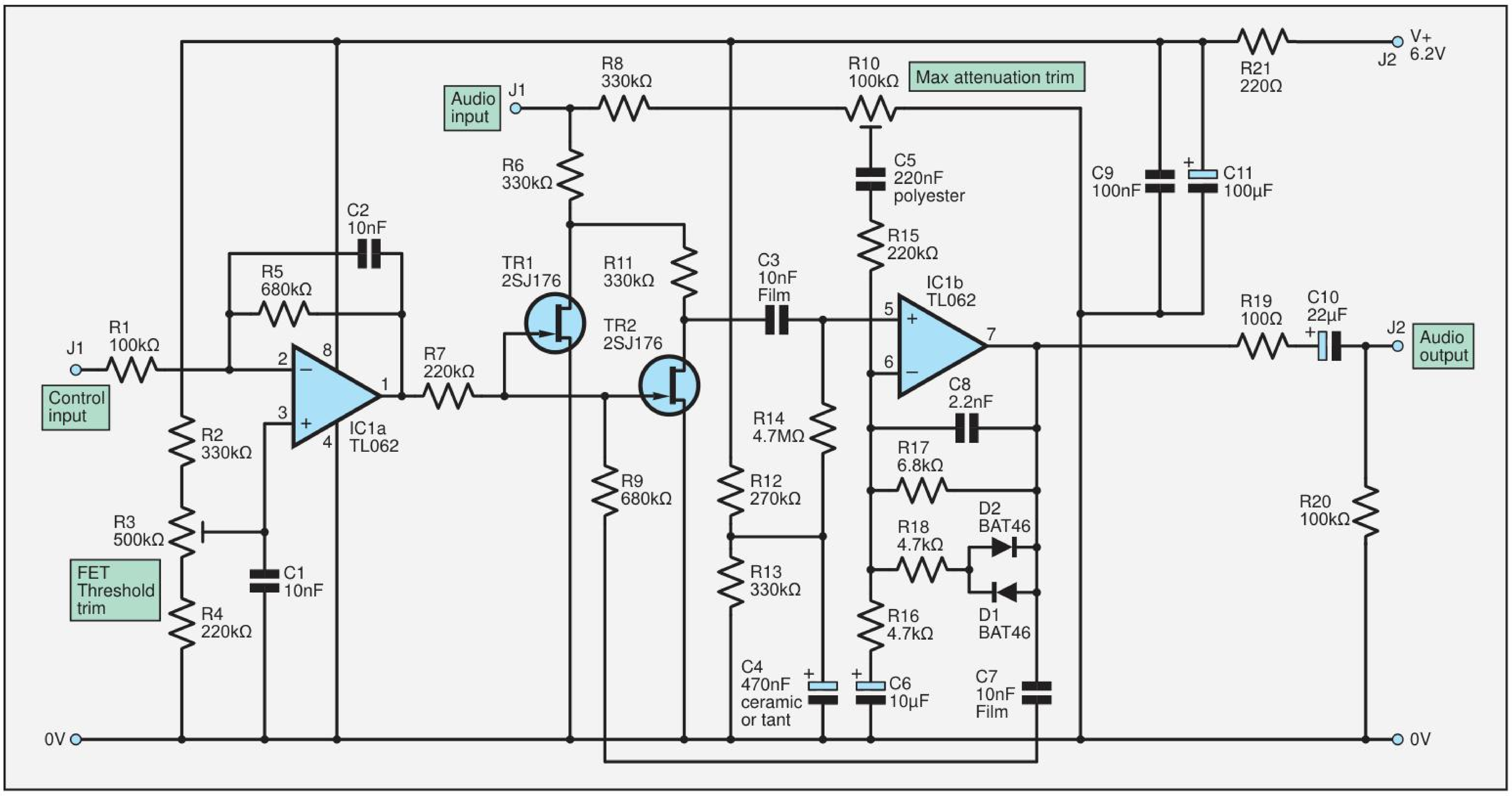

J1
Control input
R1 100kΩ
R5 680kΩ
C2 10nF
IC1a TL062
R2 330kΩ
R3 500kΩ
FET Threshold trim
R4 220kΩ
C1 10nF
R7 220kΩ
Audio input
J1
R8 330kΩ
R6 330kΩ
TR1 2SJ176
R11 330kΩ
TR2 2SJ176
R9 680kΩ
C3 10nF Film
R12 270kΩ
R13 330kΩ
R14 4.7MΩ
C4 470nF ceramic or tant
R10 100kΩ
Max attenuation trim
C5 220nF polyester
R15 220kΩ
IC1b TL062
C8 2.2nF
R17 6.8kΩ
R18 4.7kΩ
D2 BAT46
D1 BAT46
R16 4.7kΩ
C6 10µF
C7 10nF Film
C9 100nF
C11 100µF
R21 220Ω
J2
V+ 6.2V
R19 100Ω
C10 22µF
J2
Audio output
R20 100kΩ
0V
0V

Fig.31. JFET VCA circuit.

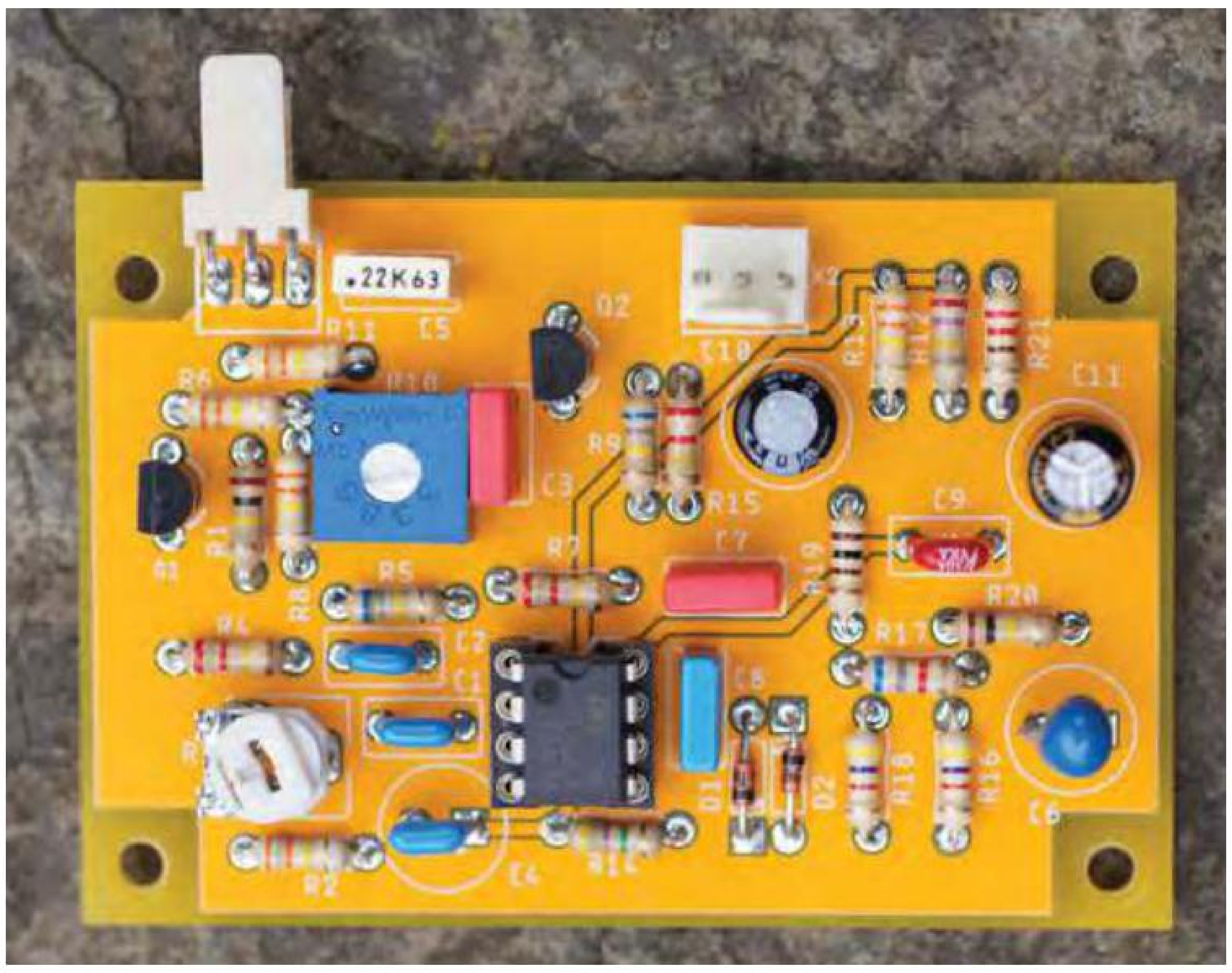


Fig.33. Completed JFET VCA PCB.

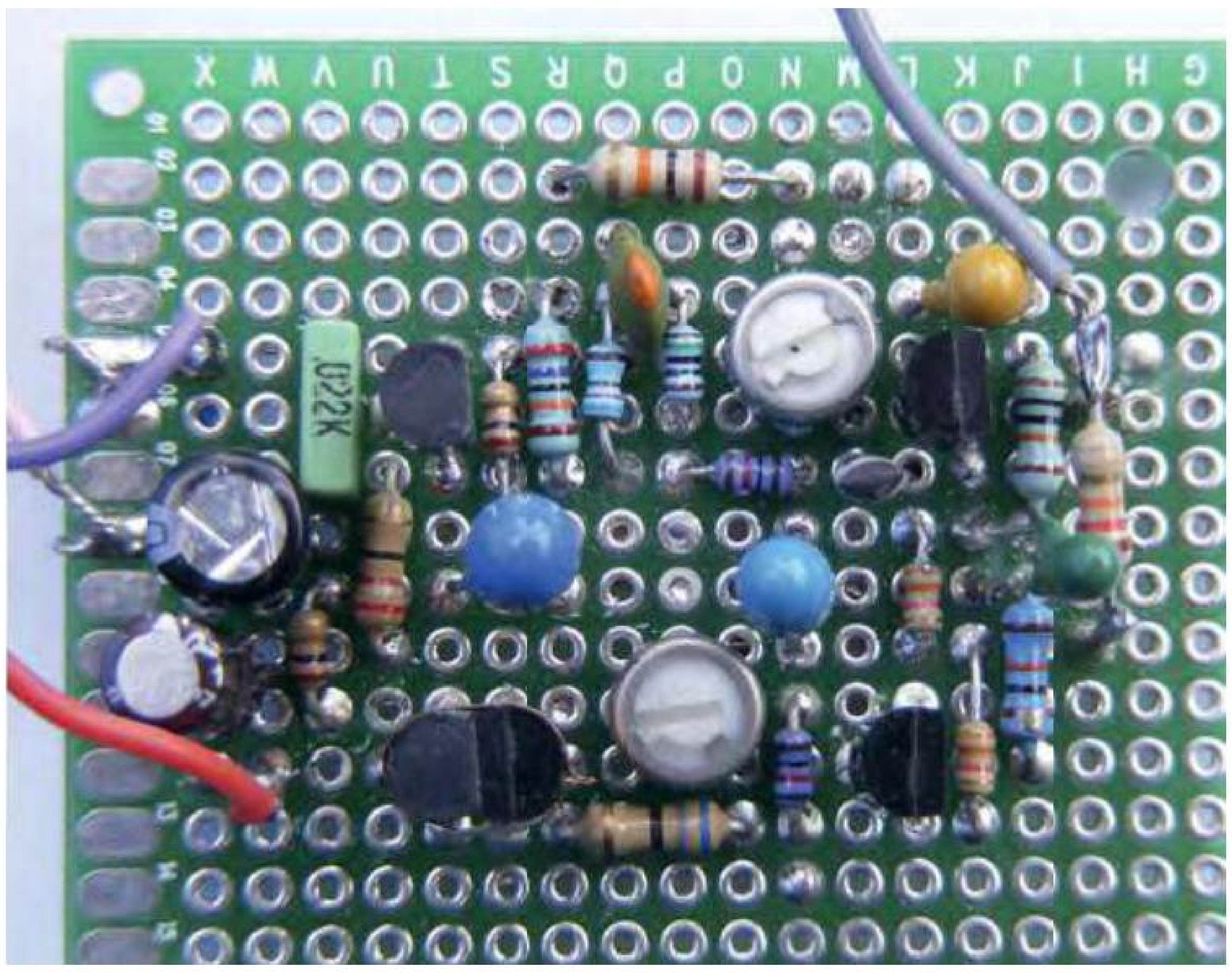


Fig.35. Prototype dedicated Theremin amplifier.

The VCA

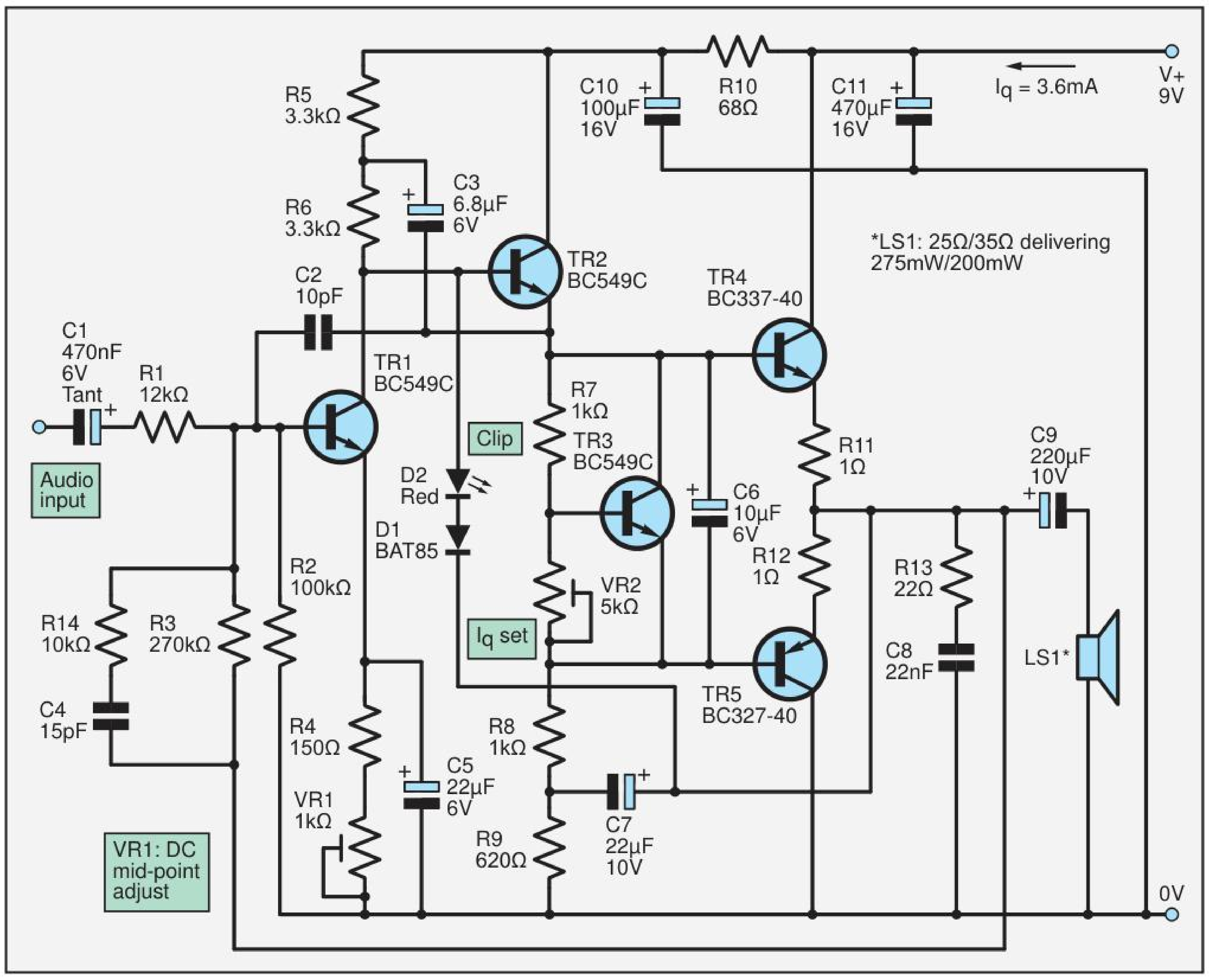
In this reasonably priced design, I'll be using a budget VCA, implemented with JFETs rather than the LM13700 transconductance op amp. The VCA circuit, shown in Fig.31, is really a voltage-controlled attenuator, which together with a dual op-amp forms the complete system.

JFETs do have some well-known problems, such as their large variation in pinch-off voltage. A preset resistor (R3) adjusts the gate bias voltage to deal with pinch-off voltage spread. Another problem is distortion due to the channel resistance of the JFET being modulated by the audio signal. This is worst when the volume is midway. This distortion can be cancelled by mixing the audio equally with the control signal on the gate via R9. Finally, all JFETs have a significant on-resistance, which means the sound cannot normally be completely turned off. Using two JFETs can eliminate this and I added another preset (R10) to trim out any remaining signal by anti-phase cancellation. This is achieved by feeding a small fraction of the audio into the inverting input of the output buffer amplifier IC1b.

In this circuit, P-channel J175/6 devices are used. P channels are 'on' or minimum resistance, when the bias voltage is 0V, giving minimum volume. A positive voltage above approximately +2.2V pinches off the JFET and the volume rises. To get maximum range, the gate is biased using R9 so the sound just goes off. If it was allowed to go all the way down to 0V there would be a large dead-band on the volume loop control range.

This volume control circuitry gives a positive play response; the closer the hand, the louder it gets. If the 'classical' Theremin response is wanted, the JFETs can be replaced with N-channel MOSFETs, such as the BS170. The FET control law is rather snappy between on and off. Interestingly, using two mismatched JFETs improves this.

As an aside, using an LM13700-based VCA, as in my *EPE* November 2018 design, with a bit of control voltage shaping will give a smoother response, suitable for a larger Theremin. This upgrade will be available soon, but for now this circuit is good enough for smaller instruments. It's also a useful board in its own right for audio limiters, switchers and educational use. The layout is shown in Fig.32 and the completed board in Fig.33.



R5
3.3kΩ
C10
100µF
16V
R10
68Ω
C11
470µF
16V
Iq = 3.6mA
V+
9V
R6
3.3kΩ
C3
6.8µF
6V
TR2
BC549C
TR4
BC337-40
*LS1: 25Ω/35Ω delivering
275mW/200mW
C2
10pF
C1
470nF
6V
Tant
R1
12kΩ
TR1
BC549C
R7
1kΩ
Clip
TR3
BC549C
R11
1Ω
C9
220µF
10V
Audio input
D2
Red
D1
BAT85
C6
10µF
6V
R12
1Ω
R13
22Ω
R2
100kΩ
VR2
5kΩ
R14
10kΩ
R3
270kΩ
Iq set
C8
22nF
LS1*
C4
15pF
TR5
BC327-40
R4
150Ω
C5
22µF
6V
R8
1kΩ
VR1
1kΩ
R9
620Ω
C7
22µF
10V
VR1: DC mid-point adjust
0V

Fig.34. Suggested amplifier circuit. You could use a TBA820 chip or similar, but this uses half the quiescent current and is an interesting circuit in its own right.

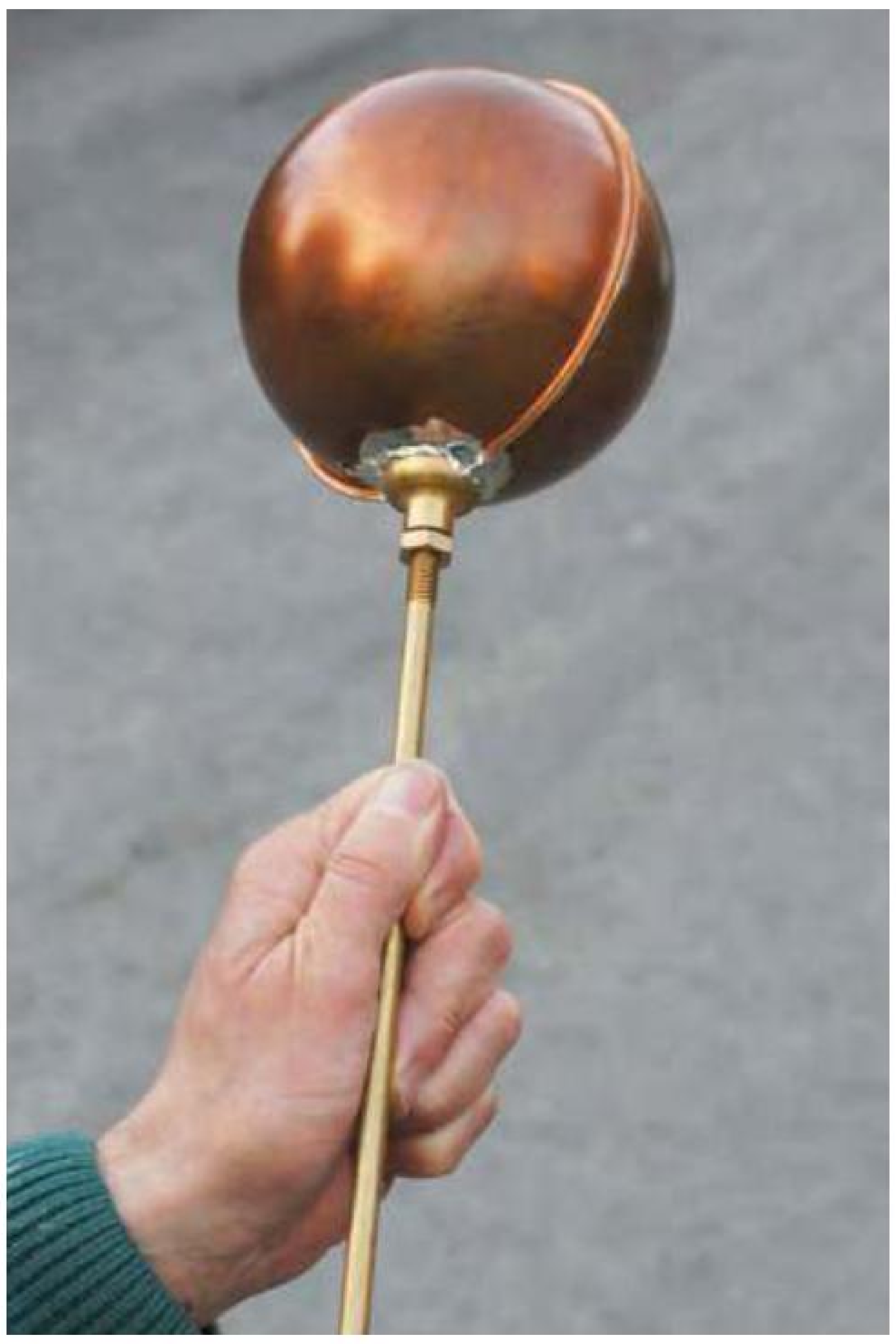


Fig.36. Copper toilet cistern balls make for interesting Theremin aerials!

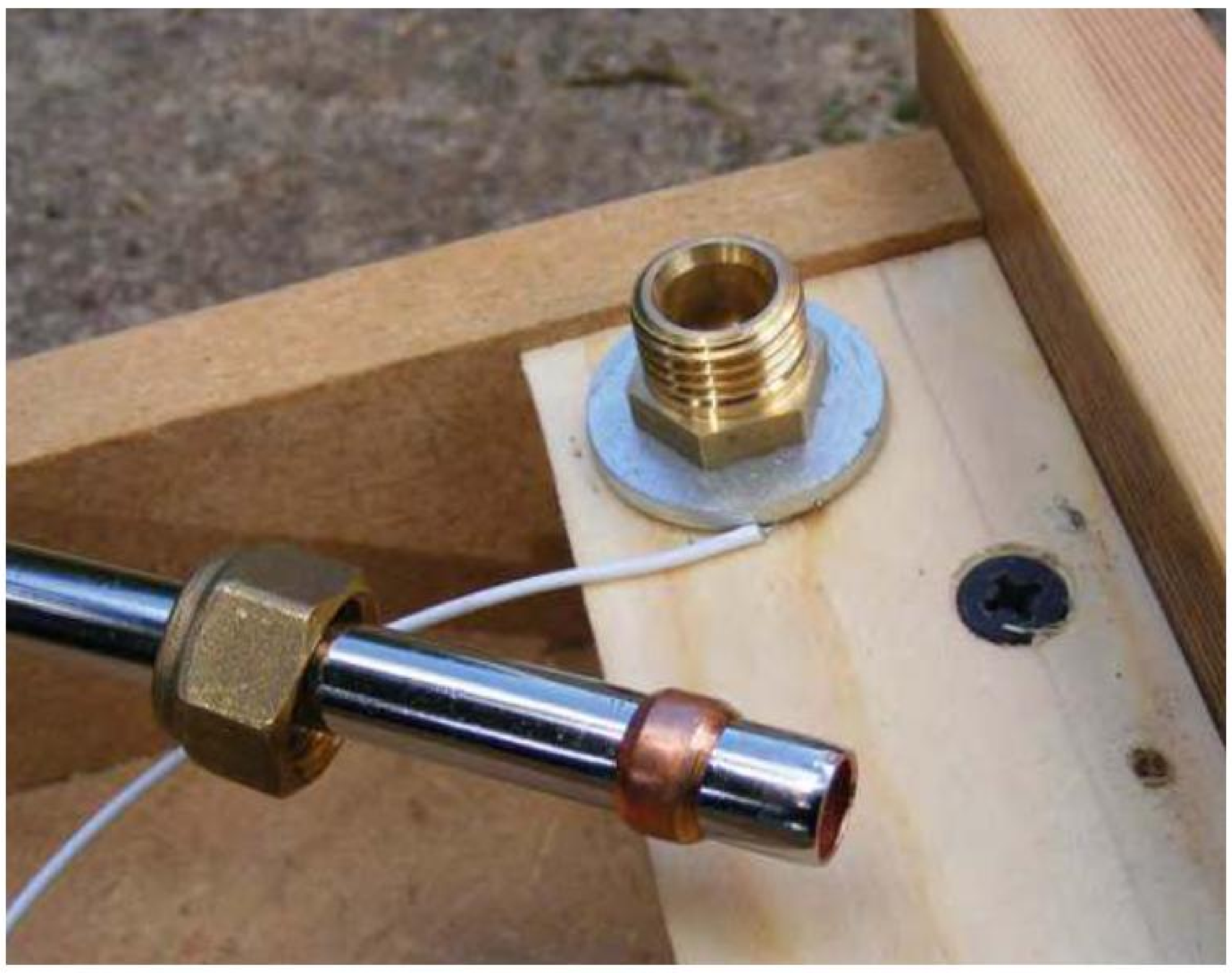


Fig.37. Chromed copper pipe for connecting gas fires make excellent aerial system.

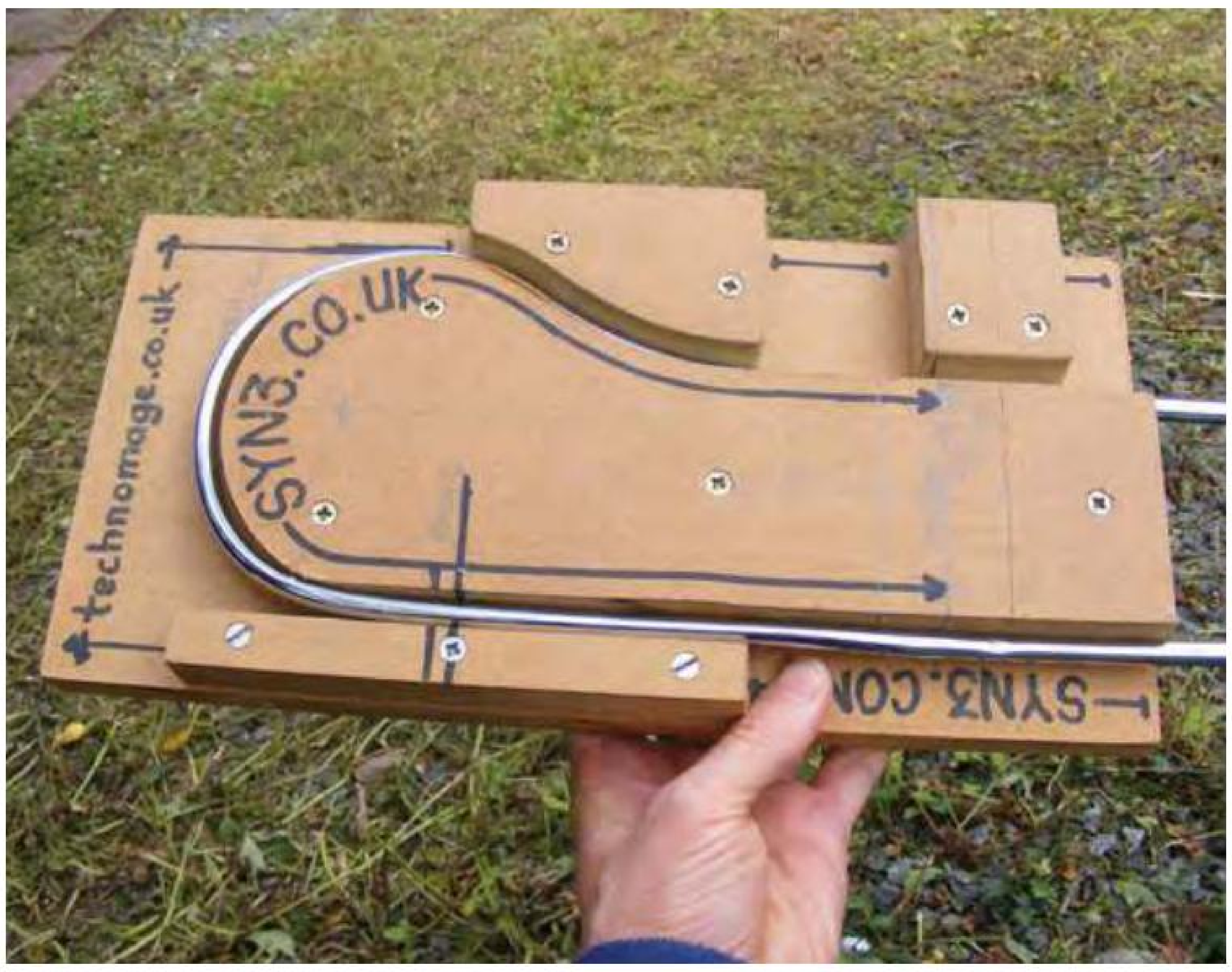


Fig.38. To make good bends in volume loop tubing, a simple jig really helps – designed by Grant Stevens for **Theremin.co.uk**

Parts list for VCA PCB

Semiconductors
TR1, TR2 2SJ175 or 2SJ176 P-channel JFETs from Mouser
D1, D2 BAT86 or BAT42 low-power Schottky diodes
IC1 TL062 or MCP6002 low-power FET low voltage op-amp

Resistors (*All 0.25W 5% carbon-film*)
R1, R5, R9 680kΩ
R2, R6, R8, R11, R13 330kΩ
R3 500kΩ preset horizontal
R4, R7, R15 220kΩ
R10 100kΩ preset horizontal
R12 270kΩ
R14 4.7MΩ
R16, R18 4.7kΩ
R17 6.8kΩ
R19 100Ω
R20 100kΩ

Capacitors (*All 5mm/0.2-inch pitch*)
C1, C2 10nF X7R ceramic
C3, C7 10nF polyester
C4 470nF X7R ceramic or tantalum
C5 220nF polyester
C6 10µF electrolytic or tantalum
C8 2.2nF NP0 ceramic or polyester
C9 100nF X7R ceramic
C10 22µF electrolytic
C11 100µF electrolytic

Miscellaneous
Molex 3-pin connectors 2 off
8-pin DIL socket

Output amplifier

The maximum output of this Theremin is around 800mV peak-to-peak or $280\text{mV}_{\text{rms}}$ or –8.8dB. This is sufficient for most chip power amplifiers, such as the LM386, TBA820. With just a line output jack it is ideal for guitar combos. If minimum power consumption is needed and relative complexity is not a problem, then the *GULP Amplifier* described in *EPE* January 2019 is ideal.

Of course, being an audio enthusiast I couldn't help but design a dedicated small discrete amplifier shown in Fig.34. It is unusual in having dual bootstrapping of both the main gain and emitter-follower driver stages for maximum efficiency. It gives 275mW output into 25Ω with 3.5mA quiescent current and 40mA max volume. I've built a prototype, shown in Fig.35 and I will offer a PCB version in a couple of months. This design includes presets for quiescent current and DC mid-point, but once you've gone down the road of building a Theremin, adjustments become a way of life. If you're in a hurry to build this design you can use perfboard and here are the components (but I'd wait for the PCB!).

Parts list for dedicated Theremin audio amplifier

Semiconductors
TR1, TR2, TR3 BC549C small-signal high H_{fe}
TR4 BC337-40 NPN medium-power output
TR5 BC327-40 PNP medium-power output
D1 BAT46/42/85 low-power Schottky diode
LED1 low-current/high-brightness 3mm red LED

Resistors (*All 0.25W 5% carbon-film unless otherwise stated*)
Volume control/power (if fitted) 5kΩ potentiometer (log) with switch
R1 12kΩ metal film
R2 100kΩ metal film
R3 270kΩ metal film
R4 150Ω
R5, R6 3.3kΩ metal film
R7, R8 1kΩ
R9 620Ω
R10 68Ω
R11, R12 1Ω
R13 22Ω
R14 10kΩ
PR1 1kΩ TO5 outline trimmer
PR2 5kΩ TO5 outline trimmer

Capacitors
C1 470nF polyester/tantalum 6.3V
C2 22µF electrolytic or tantalum 3V minimum
C3 6.8µF electrolytic or tantalum 6.3V minimum
C4 100µF electrolytic
C5 22µF 10V electrolytic or tantalum
C6 22nF polyester
C7 220µF 10V electrolytic
C8 470µF 16V electrolytic
C9 15pF NP0 ceramic
C10 8.2pF NP0 ceramic

Miscellaneous
Loudspeaker 16 to 50Ω 2.5 inch/57mm to 5 inch 120mm paper cone low power. I used a EuroTec 80mm SR27255 25Ω 2W with EuroTec matching grill (both available from author).

'Aerial' physical construction and mounting

Since the 'aerials' are just capacitive surfaces, there is no critical wavelength tuning and their construction and design is only limited by the constructor's imagination. I have even used copper toilet cistern balls, shown in Fig.36. The 'chromed gas-fire pipe' approach popularised by Moog is the most effective system for large Theremins (Fig.37 and Fig.38) while 'rubber duck' aerials work well for smaller designs, such as the *Eclipse* shown in Fig.39. Of course each aerial's capacitance must be allowed for in the design. This often means adding or removing capacitance across the inductors. This

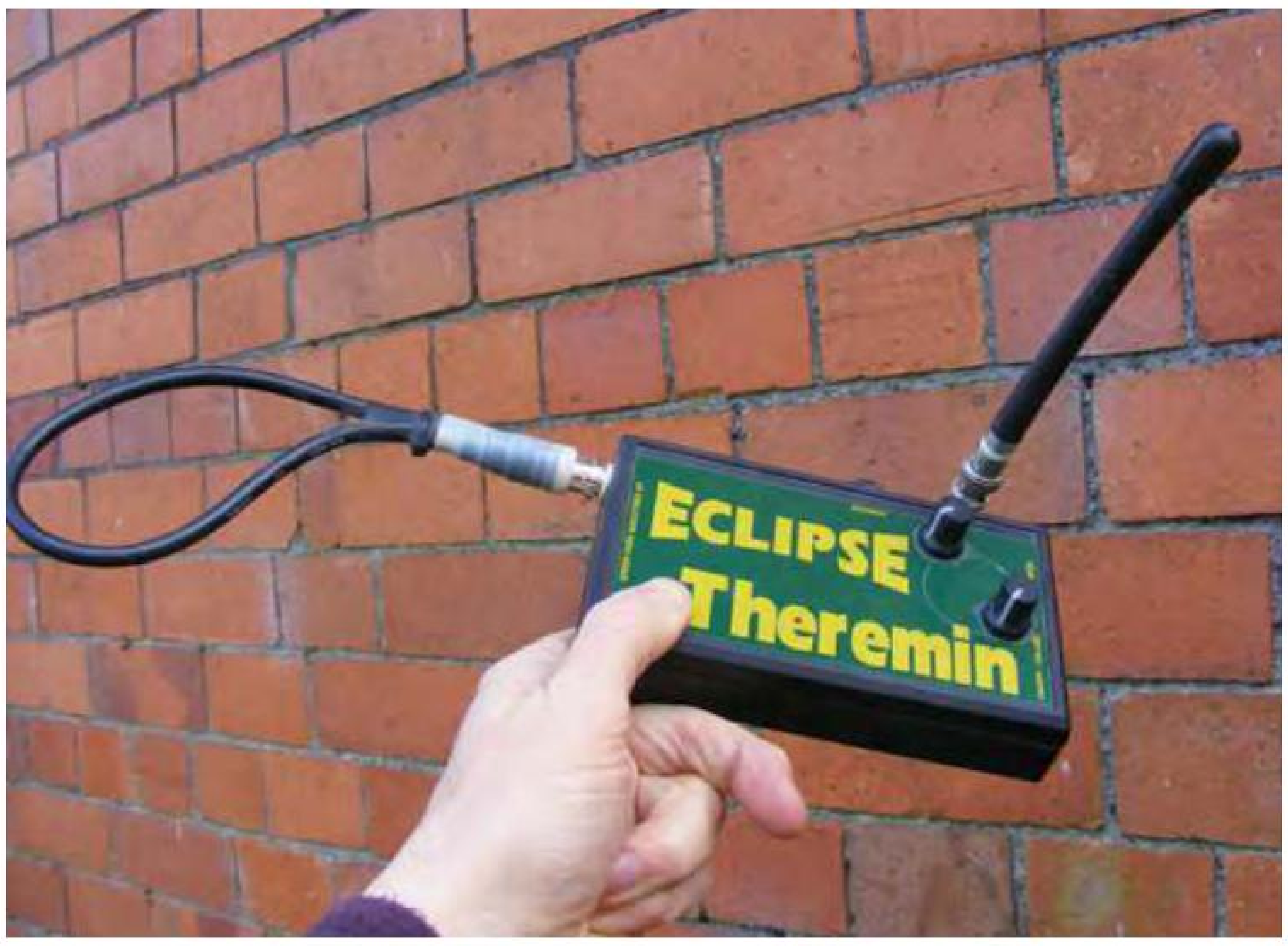


Fig.39. ‘Rubber duck’ aerials for portable communications make good pitch aerials for small Theremins. They are usually detachable thanks to their BNC plug bases.

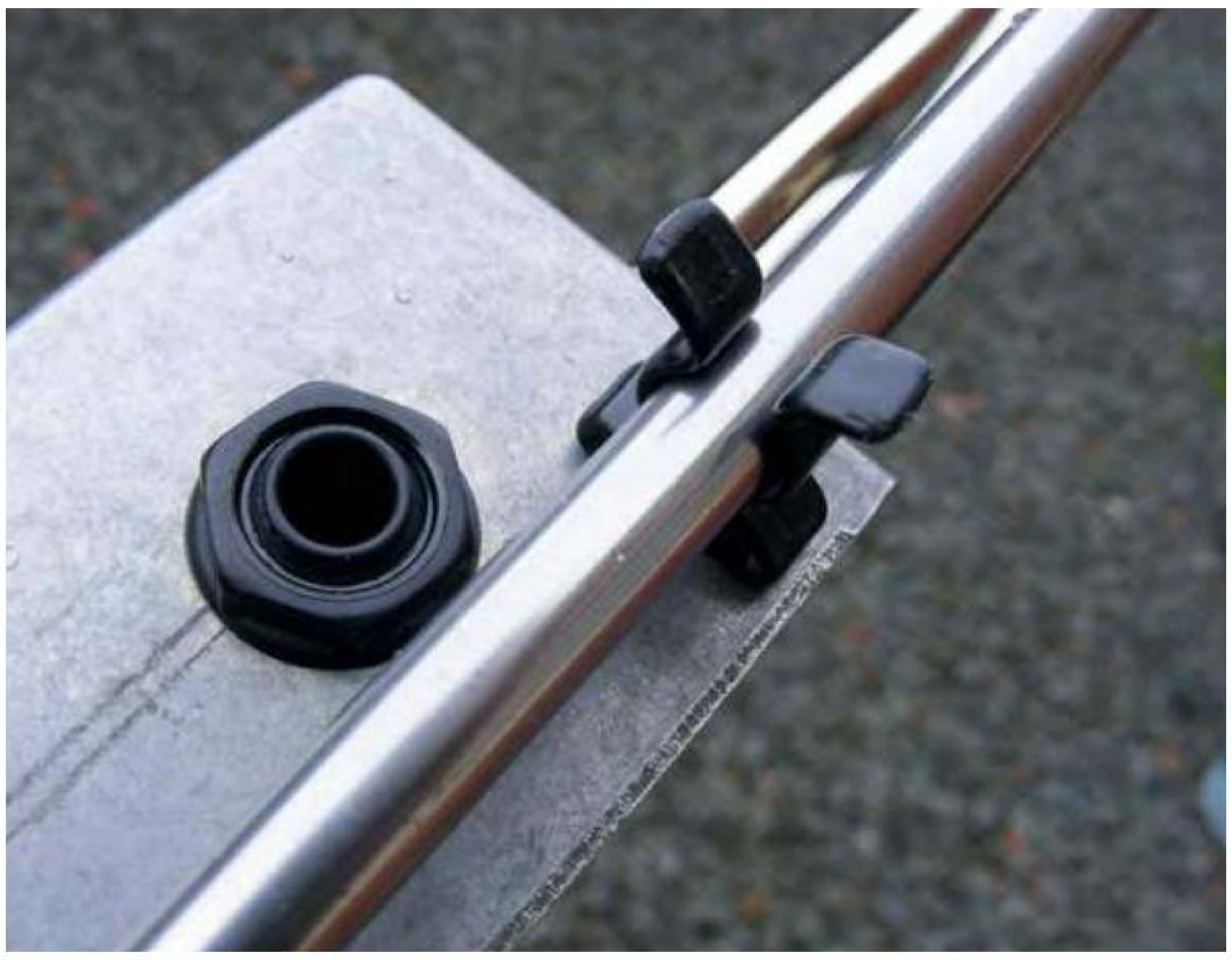


Fig.40. Use tool clips to store detachable aerials when transporting the Theremin.

is accomplished by adjusting padder capacitors C5 and C11 on the pitch board and C4 on the volume board. An ultrasonic output due to mistuning is the most common reason for a Theremin giving ‘no sound’.

Note that it is normal for the volume plate to respond to vertical hand movements and the pitch plate to horizontal. This helps minimise interaction between the two plates.

The pitch aerial is typically on the right for right-handed players and is normally detachable, often being mounted in 3/8-inch metal clips when not in use (Fig.40). The volume loop can conveniently double as a carrying handle – see Fig.41. Cable glands help clamp the aerial tubing in place, as shown in Fig.42. Gas pipes are available from plumbers’ merchants and Screwfix.

Loading inductors

Sometimes relatively large inductors are placed in series with the control plates. This spreads out the range and makes the control characteristic more linear. Normally, the notes get much closer together as the player’s hand moves towards the plate. These coils act as a series resonator with the aerial and make it appear bigger. It is worth experimenting to find the optimum value for a given aerial and oscillator frequency. It is essential loading inductors have minimal self-capacitance. Moog used expensive pie-wound Miller inductors (now made by Bourns) in his *Etherwave Theremin*, as shown in Fig.43. I have found long-wave ferrite-rod aerial and several series connected smaller coils to work well.

Interference

The loading coils also help block RF interference from mobile phones and switch-mode power supplies that can play havoc with Theremins. In a serious performance one generally has to ask people to turn their phones off. Running the oscillators at a higher power also helps. In the *Elysian Theremin* I run the oscillators on a 15V rail. This also allows the use of BC182L oscillator transistors. It might be thought

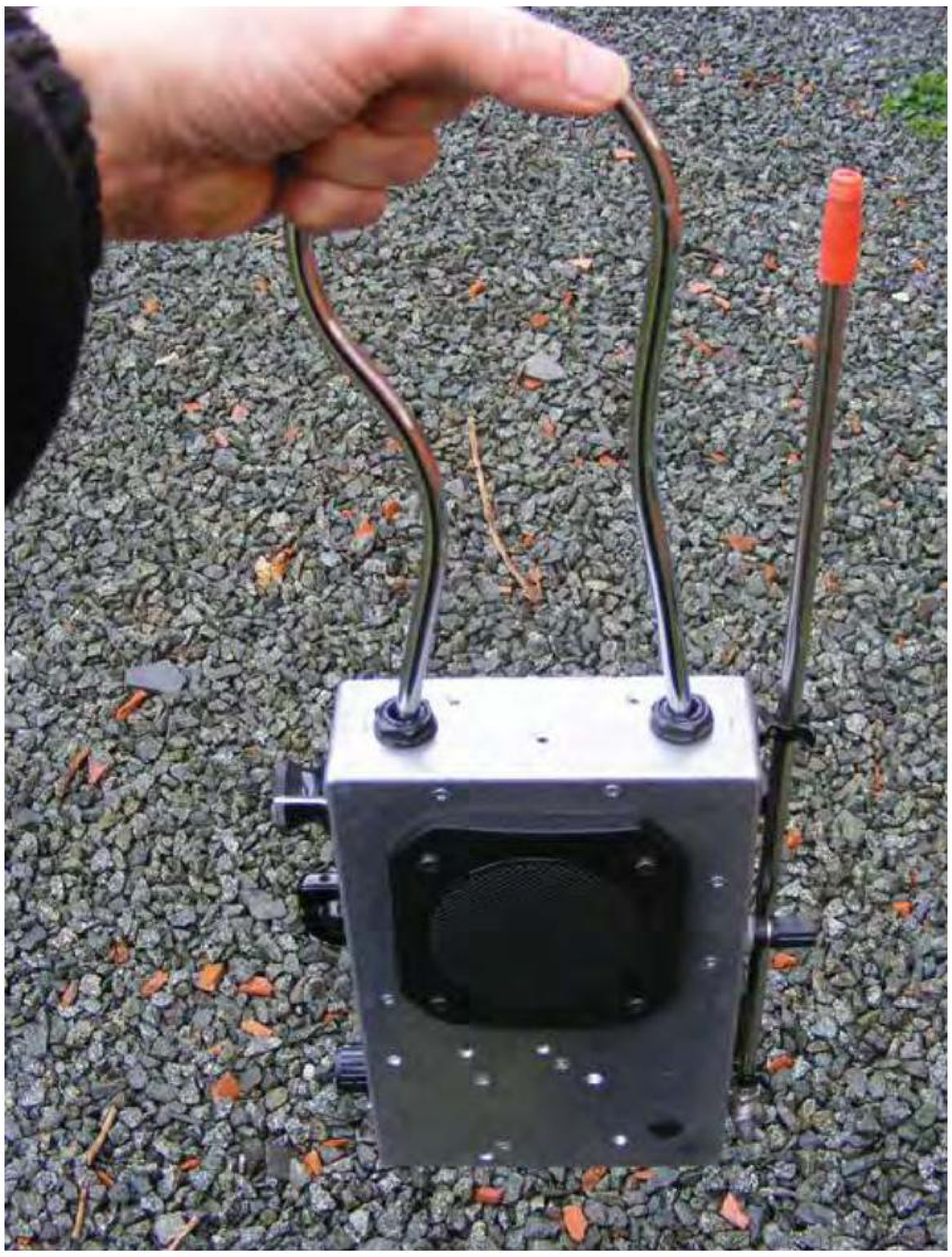


Fig.41. The Theremin volume loop doubles as a handle.

Sourcing PCBs and parts

PCB Eagle CAD files for the pitch, volume and VCA boards are available for download from the August 2019 page of the *PE* website, and a set of three PCBs is available from the *PE PCB Service* (see page 78).

Some of the parts described in the articles can take a bit of hunting down. To make life easier we are offering a pack of parts with the PCBs. The pack includes:

Circuit	Component	Value	Number
Pitch board	Inductor	100μH	2 off
Pitch board	Inductor	270μH	2 off
Pitch board	BJT	BF199	2 off
Pitch board	Trim cap	40pF	1 off
Vol/VCA boards	JFET	BF244	2 off*
Vol/VCA boards	JFET	J176	2 off
Vol/VCA boards	Inductor	82μH	1 off
Vol/VCA boards	Inductor	39μH	1 off
Vol/VCA boards	Trim cap	40pF	1 off

* (also for pitch board – see *PE*, page 55, July 2019)

The total price for the pack is £15 including VAT, p&p

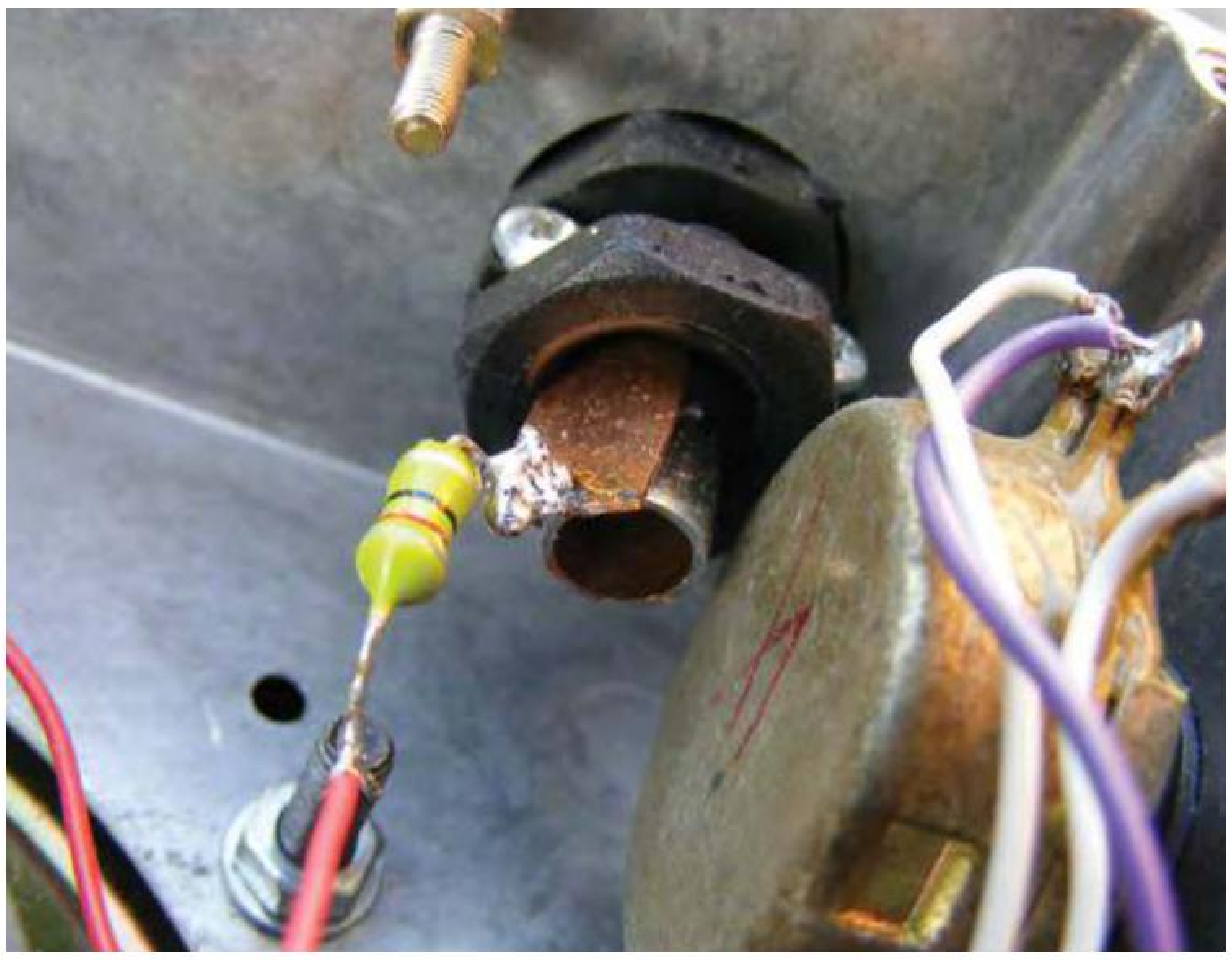


Fig.42. Cable glands make a great way to fix aerial piping. Note the technique of clamping an easy-to-solder copper strip in good electrical contact with the hard-to-solder chromed copper pipe.

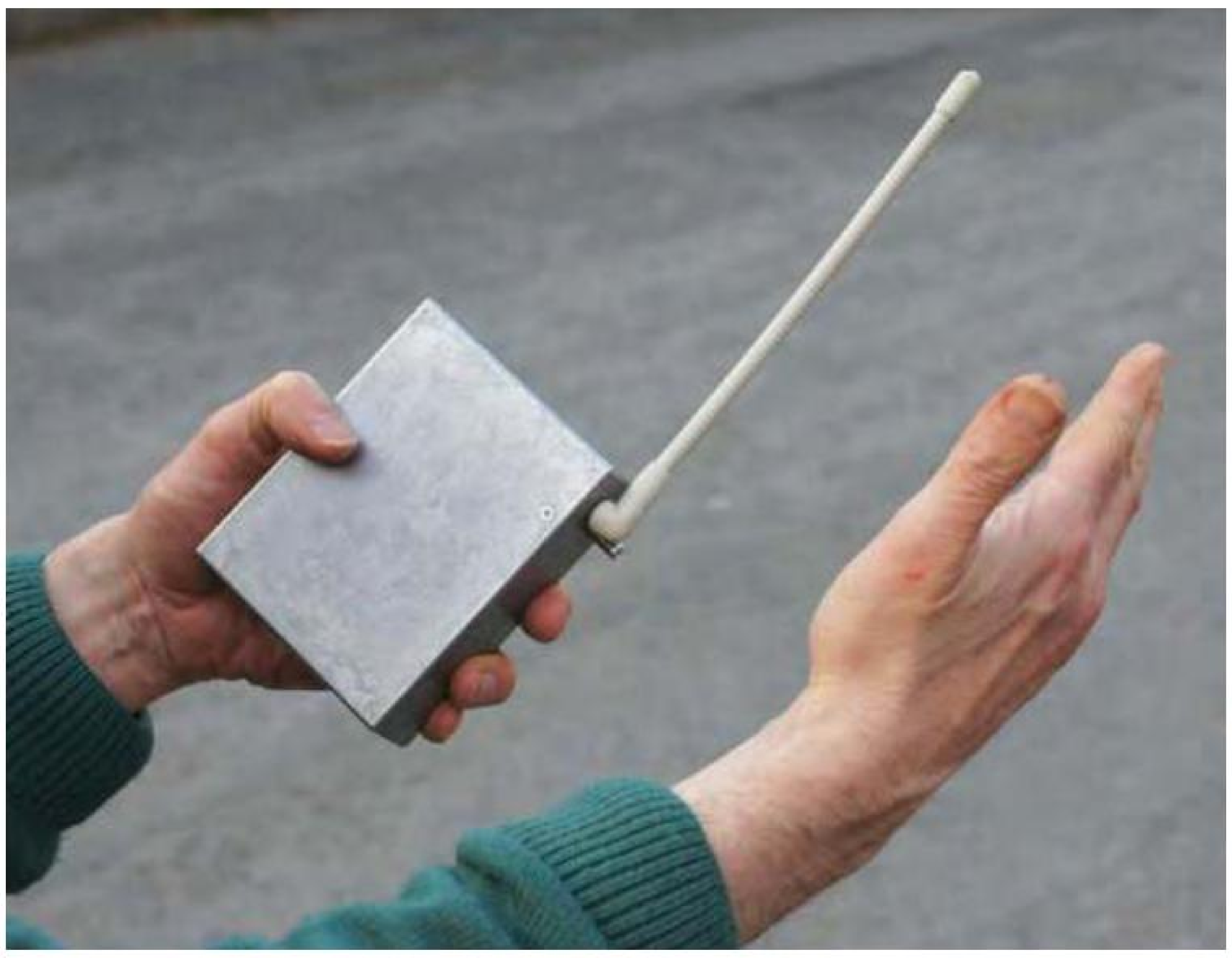


Fig.44. A metal case provides an excellent earthing path to the player for hand-held pitch-only Theremins. (Photo: thanks to Harvey Rothman)

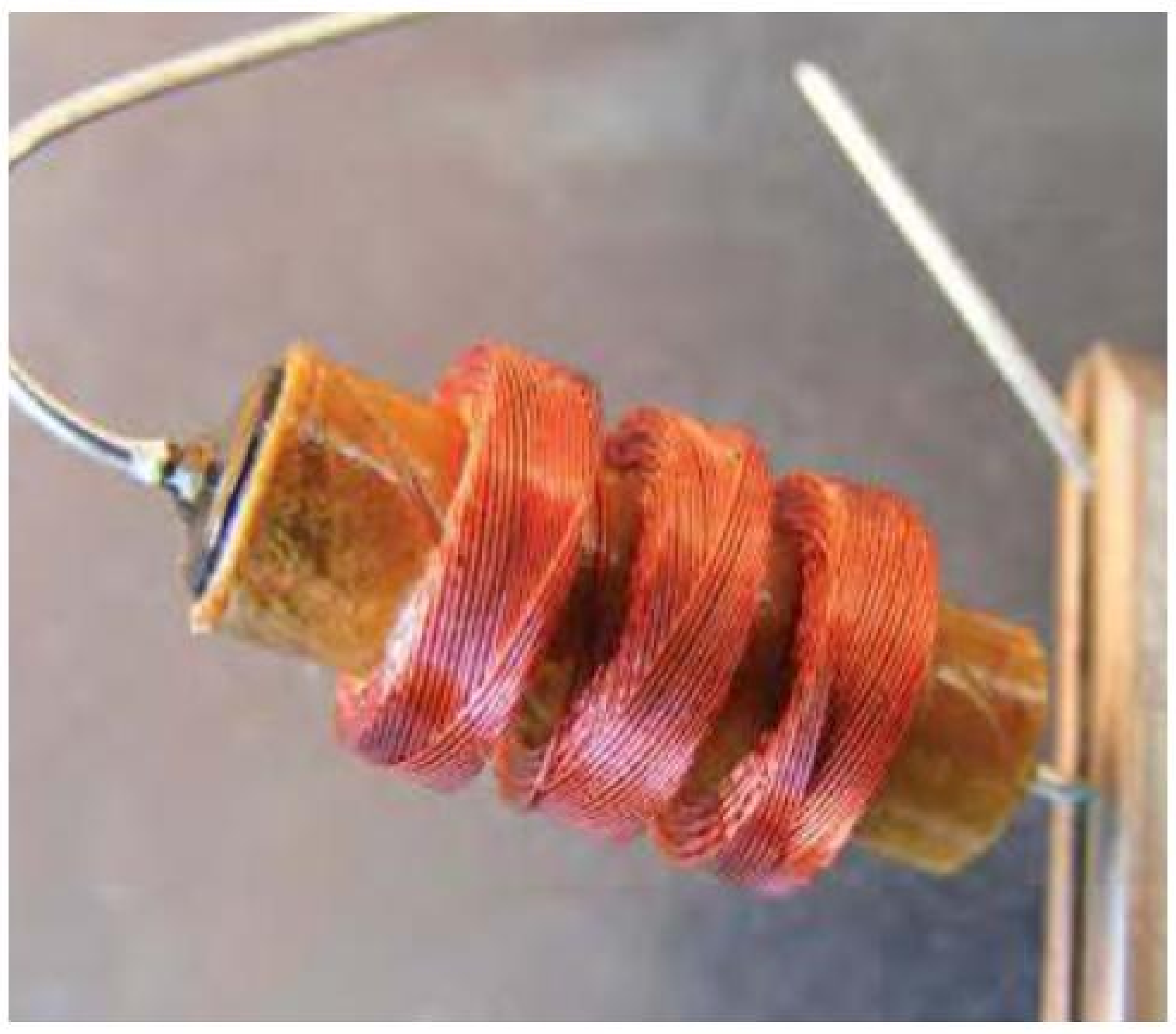


Fig.43. Pie-wound coils from Miller Bourns have minimal self-capacitance and make excellent loading coils.

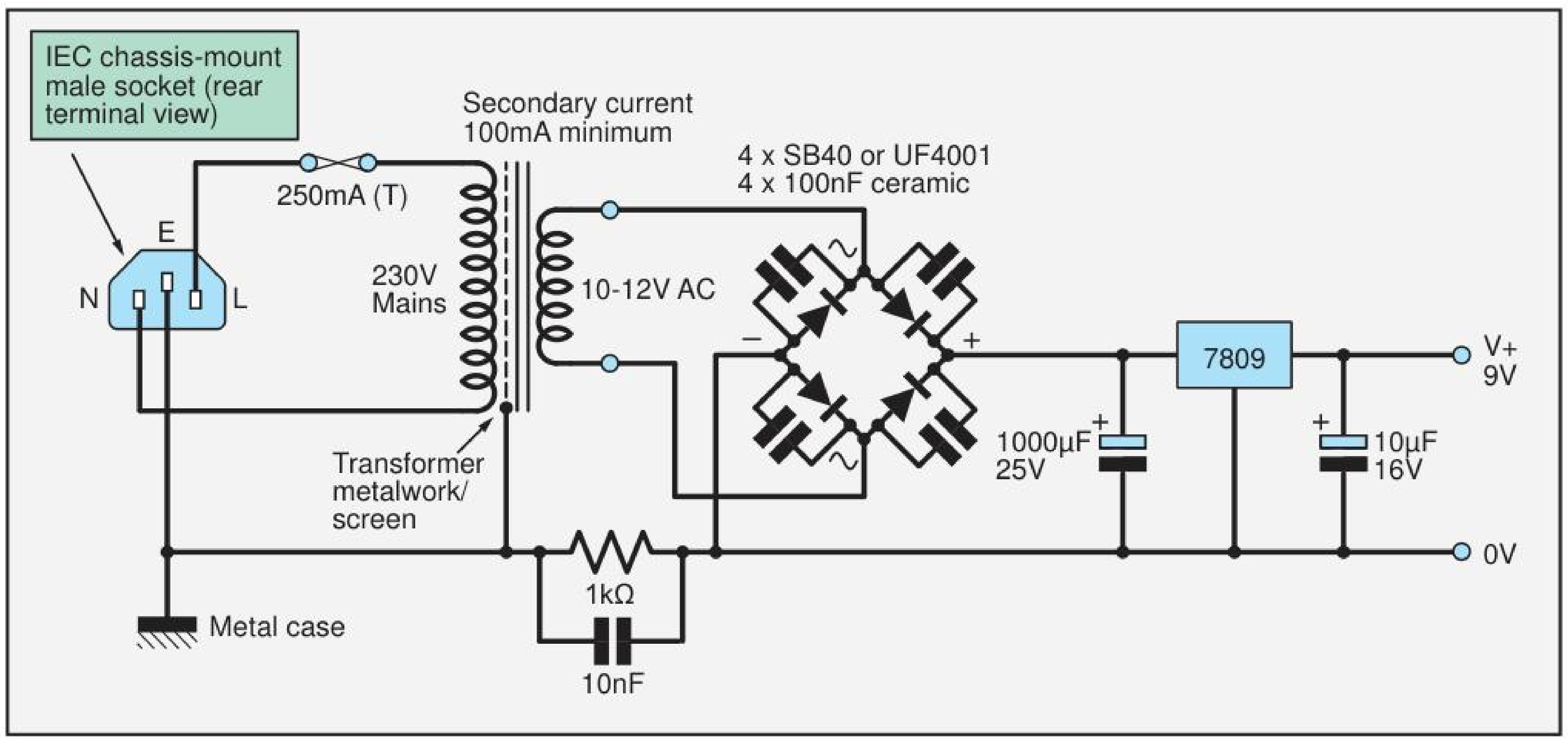


Fig.45. A suitable Theremin power supply circuit. Note the use of Schottky diodes with snubber capacitors to reduce hum-modulated RF emissions.

that Theremins themselves can cause interference. I have noticed they can cause a whistling on AM radios if placed within a few feet, but because they are low-power sine-wave emitters they don't cause any problems. I took an *Etherwave Theremin* and did a full CE test on it in the University of South Wales EMC room and it was well below troublesome thresholds.

The case

Normally, an electrically non-conducting plastic or wooden case is used for Theremins, since the proximity of earthed structures affects the tuning. Surprisingly, a metal case can be used for a Theremin, but only if its additional capacitance is accommodated and it is properly earthed. This is easy to arrange if the unit is used with a UK mains supply. If battery operation is contemplated, an earthing terminal for the case is essential. With hand-held Theremins, a metal case can be used as a convenient way of earthing the player's body, giving increased range – see Fig.44.

Power supply

Theremins are similar to old AM radios in many ways and they are also sensitive to power supply switching noise. The CE regulations don't cover interference below 1MHz, so this is a case where one has to make a dedicated Theremin power supply. Using a standard DC 'wall-wart' just results in horrid modulation hum. Such supplies also have no earth connection (they are floating) and thus capacitively couple mains interference, producing random note glitches. It is necessary to bypass each diode in the bridge rectifier with capacitors to reduce RF switching noise. If Schottky diodes or fast recovery diodes are used, the RF is reduced even more. This Theremin will work on a PP3 9V battery, which is one way of getting round power supply problems. If the power supply is in the same box as the Theremin a low-magnetic-field toroidal transformer will have to be used. A suitable circuit is given in Fig.45, the completed unit shown in Fig.46. I will present a suitable mains supply PCB (along with the dedicated amplifier discussed above) in a couple of issue's time.

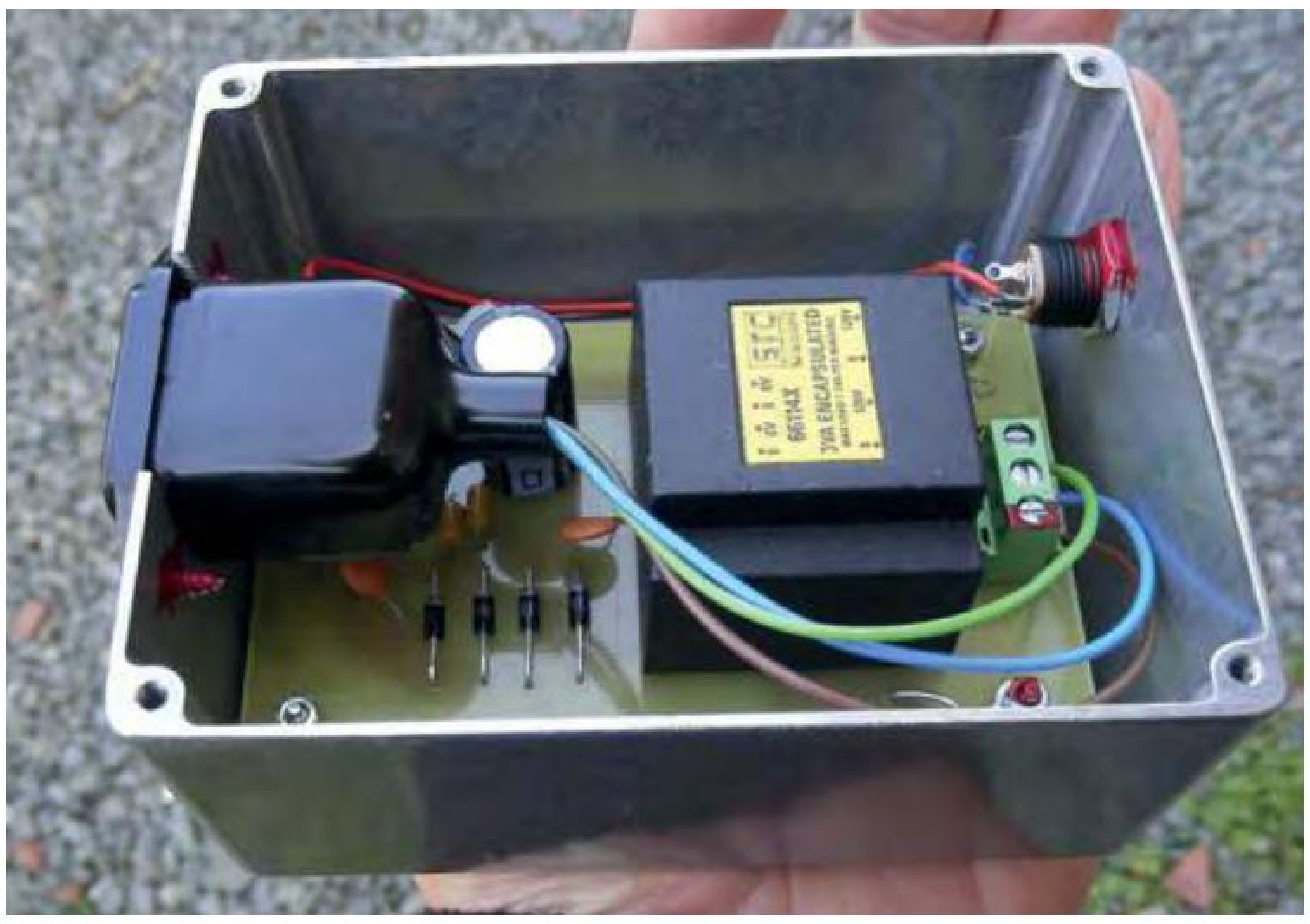


Fig.46. Theremin power supply unit.

Max's Cool Beans

By Max the Magnificent

Nixie party, 4-bit computers and a stability question

I currently hang my hat in the city of Huntsville, Alabama in the US, but I'm originally from Sheffield in Yorkshire, England. A couple of times a year, I bounce over to Sheffield to visit my dear old mum. On the last Friday before I return to America, a bunch of my techno-geek chums travel from around the country to congregate at my brother's house. We spend the day showing off our latest creations while mum provides appropriate 'Ooh' and 'Aah' sound effects, as required.

Steampunk Nixie tubes

Regular attendees include Matt Pulzer, who is the editor-in-chief of *Practical Electronics*, Paul Parry of Bad Dog Designs (**https://bit.ly/2KphoLt**), and Pete Virica of PV Electronics (**https://bit.ly/2Ky2pRs**). Bad Dog Designs specialises in creating Steampunk artifacts that boast chronomatic functionality, while PV Electronics is known around the world for its printed circuit boards and component kits used in Nixie-tube-based clocks.

A special visitor to our most recent conclave was Dalibor Farny (**https://bit.ly/2FAcI6K**) who hails from the Czech Republic. Dalibor has established a world-wide reputation for his handcrafted Nixie tubes (**https://bit.ly/2QTf5ni**). In particular, Dalibor focuses on his R|Z568M tubes (the 'R' stands for 'Resurrection'), which are about 100mm tall and 50mm wide. These bodacious beauties are pin-compatible with the classic Z568M tubes, which were widely recognised as being the most attractive Nixie tubes ever made.

Dalibor's R|Z568M tubes typically feature stainless steel or satin black bases, while their internal structures are nickel coloured. When I was first introduced to Dalibor by Paul a few years ago, I heard whispered rumors of a special batch of Steampunk renderings with bronze bases and copper anodes that were in the process of being created. I immediately contacted Dalibor and asked him to add me to the list.

In the end, fabricating these little scamps posed many challenges, and Dalibor ended up with only 20 Steampunk tubes that met his exacting standards. Paul acquired six for his Wilson Robot project (**https://bit.ly/2XuPALt**) and six for his Bridge clock (**https://bit.ly/2wGX1DA**), while I snapped up the remaining eight for my own ongoing chronographic extravaganza (**https://ubm.io/2WsAiKO**). Since Dalibor has no plans to create any more of these Steampunk marvels, I think it's fair to regard them as being collectors' items.

Fig.1. Max (left) with Czech Nixie tube wizard Dalibor Farny.

Is that the time?

Do you recall my waffling on in a previous *Cool Beans* column (*Practical Electronics*, Feb 2019) about my *Countdown Timer* project? This is going to use 12 Lixie displays (**https://bit.ly/31d9Inx**) to present the years, months, weeks, hours, minutes, and seconds to my 100th birthday (29 May 2057, save the date). Following this Frabjous Day, the timer will start to countdown to my 110th birthday, and then my 120th, and so forth. If I can't attend any of these auspicious occasions for any reason (say I'm busy kayaking up the Amazon, for example), then the timer will provide a reminder to my family to hoist a glass in my name.

Fig.2. Master carpenter and *Countdown Timer* cabinet builder, Bob Lokey.

One point is that, as much as I like watching this sort of thing – 'Show me a flashing LED and I'll show you a man drooling,' as I always say – even I will get bored watching a simple countdown sequence after the first year or so. Thus, among other things, the timer will toggle between displaying the time remaining to my 100th birthday, the current day and the time, and the amount of time with which I've graced this planet with my presence.

One big consideration is the case used to host the display. I fear a cardboard box simply won't do things justice. No indeedy-doody, this little beauty demands to be presented with panache. Thus it was that I recently spent a happy weekend hanging out at the workshop of my friend, master carpenter Bob Lokey. As I wrote in a recent column (**https://bit.ly/2XDZJVW**), Bob commenced work on

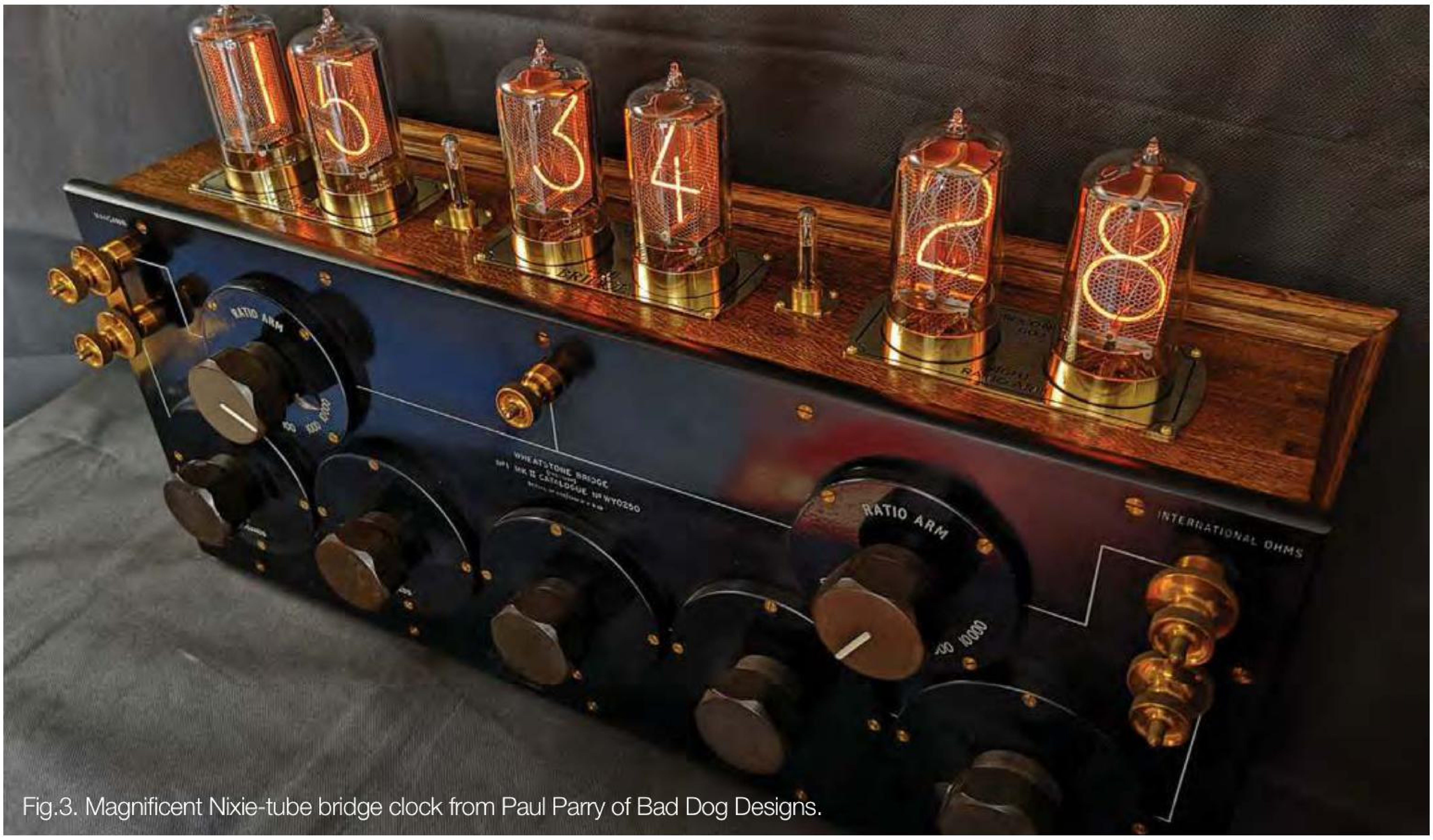


Fig.3. Magnificent Nixie-tube bridge clock from Paul Parry of Bad Dog Designs.

the case itself, while I did my best to make encouraging noises and offer useful suggestions. All I can say is that when this case has finally been fabricated, sanded, stained, waxed, buffed and polished, it's going to be a thing of beauty to behold (yes, of course I'll be flaunting pictures in a future column).

The mighty teensy

As you may know, I have a soft spot for simple microcontroller development kits, like 8-bit Arduino Nano, Uno, and Mega-based boards with their limited memories running at only 16MHz. In fact, I've primarily used these processors in my hobby projects over the past few years because I enjoy the challenge of working within their limitations, using cunning coding tricks to minimise memory utilisation, while squeezing the last drop of computational power out of each clock cycle.

On the other hand, there comes a point when it's time to stop banging your head against the wall. In the case of my *Countdown Timer*, I've been cogitating, pondering and ruminating (don't worry, I'm a professional) on a variety of temptingly tasty effects. I want to focus my efforts on developing these visual treats rather than scrimping and scraping to satisfy the limitations of my processing platform.

In short, I've decided to use a Teensy 3.2 breakout board (**https://bit.ly/2Xvh4R5**) along with an OctoWS2811 adaptor board (**https://bit.ly/2WsyAEO**) and the OctoWS2811 LED Library (**https://bit.ly/2QQOwyL**), all of which are the brainchildren of Paul Stoffregen.

The Teensy 3.2 features a 32-bit Arm Cortex-M4 processor with 256KB of Flash and 64KB of RAM running at 72MHz. Since a single Teensy 3.2 is capable of driving around 4,000 WS2811, WS2812 or WS2812B tri-colored LEDs (like the ones used in my Lixie displays), it's more than capable of driving my *Countdown Timer*. Of particular interest is the fact that the Teensy employs an 8-bit DMA engine to drive up to eight strands of LEDs simultaneously, thereby leaving the main processor free to concentrate on calculating and controlling my capriciously cunning effects.

4-bit HRRG Computer

As we discussed in an earlier column (*Practical Electronics*, May 2019), another hobby project I'm working on is the 4-bit *HRRG* (Heath Robinson, Rube Goldberg) *Computer*, the physical realisation of which will encompass a variety of implementation technologies, including relays, vacuum tubes, transistors, and jelly-bean integrated circuits, along with mechanical, magnetic, pneumatic and fluidic logic.

My cohort on this project is my chum Joe Farr, who was also in attendance at the aforementioned techno-geek gathering. Joe is currently focused on creating a virtual version of the *HRRG Computer* in the form of an emulator, while I'm concen-

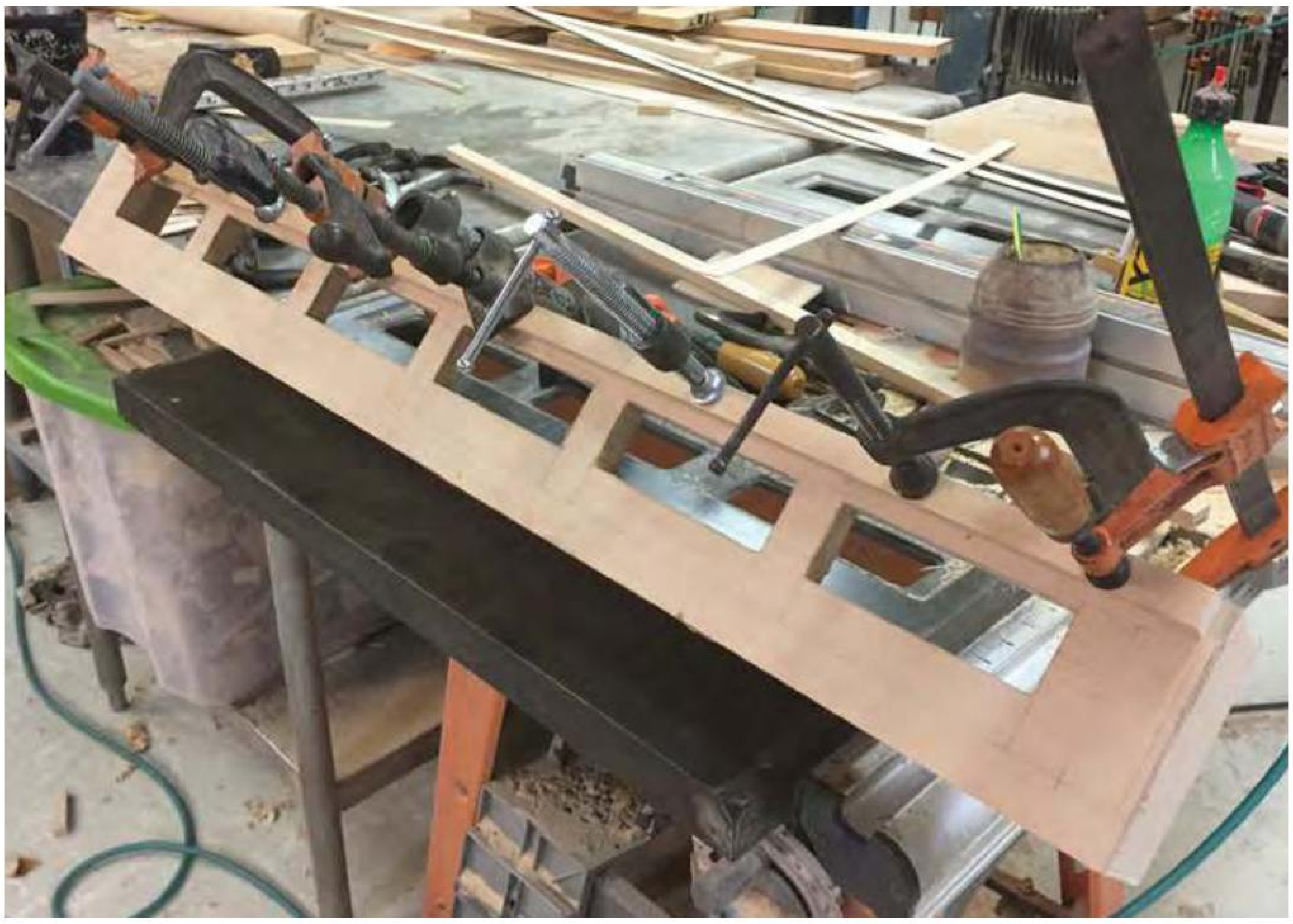


Fig.4. *Countdown Timer* cabinet under construction.

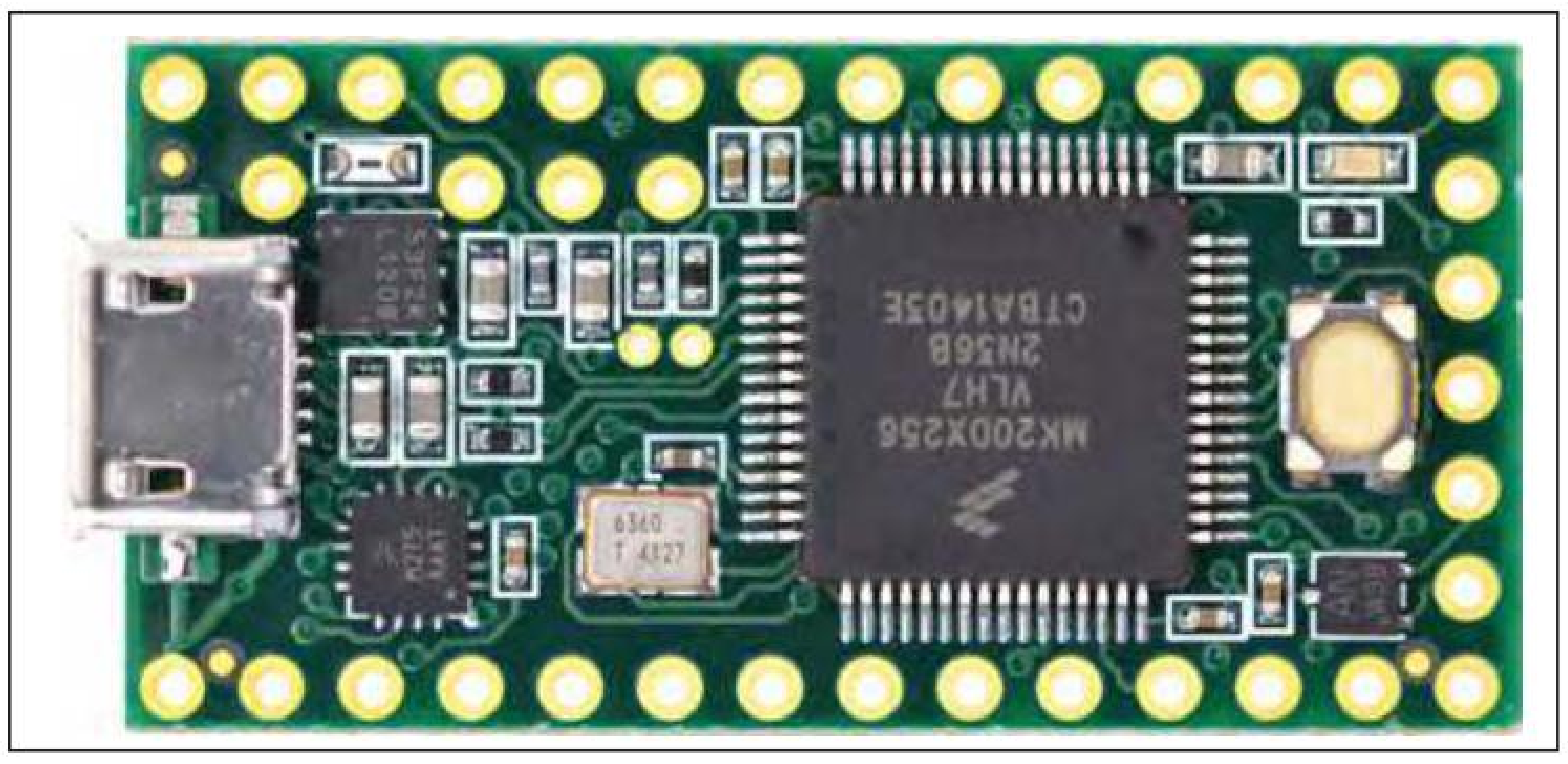
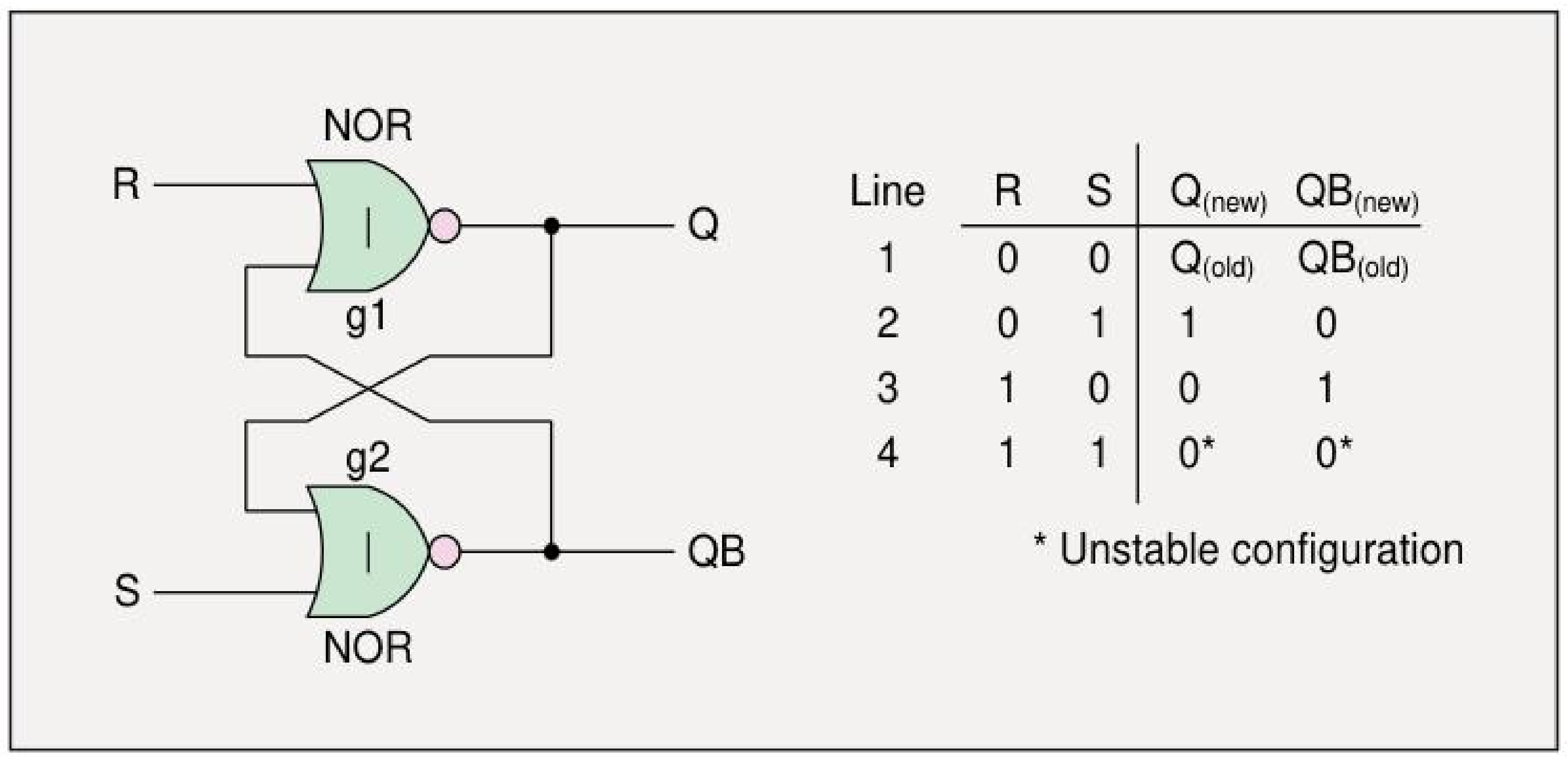


Fig.5. The Teensy 3.2 can drive around 4,000 tri-colored LEDs.



Line	R	S	$Q_{(new)}$	$QB_{(new)}$
1	0	0	$Q_{(old)}$	$QB_{(old)}$
2	0	1	1	0
3	1	0	0	1
4	1	1	0*	0*

* Unstable configuration

Fig.7. Forming an SR latch from two back-to-back NOR gates.

trating on the physical implementation of this little scamp from the switch-level up.

As part of this project, I realised that I had never really considered how microcontrollers addressed the problem of metastability caused by reading asynchronous signals from the outside world. Actually, this is a really interesting topic (trust me, have I ever lied to you before?), so let's take some time to ponder this in a little detail.

Orrible oscillations

One of the ways electronic systems store ('remember') data values is in registers, each element of which can hold a single binary digit, or 'bit', which can be 0 or 1. At the heart of each register is an asynchronous SR (set-reset) latch (or something equivalent), which may also be referred to as an RS (reset-set) latch. One way to make an SR latch is by using two back-to-back NOR gates (Fig.7).

From Line 3 of the truth table we see that if the R ('reset') input is in its active 1 state, then the output Q is 'reset' to 0. Alternatively, from Line 2 of the truth table we see that if the S ('set') input is in its active 1 state, then output Q is 'set' to 1. Under normal conditions, the QB output adopts the opposite (complementary) logical value to the Q output.

When both the S and R inputs are in their inactive 0 states, as shown in Line 1 of the table, the values on the outputs reflect whichever of the S or R inputs was last active. As we shall see, the SR latch's ability to 'remember' whichever input was last active is based on feeding back the output from each gate as an input to its companion.

Now consider Line 4 of the table. If *both* S and R inputs are in their active 1 states, then both Q and QB outputs are driven to logic 0 values. Unfortunately, this is an unstable configuration. If we move from Line 4 to either Line 2 or Line 3, then all will be well, but if we move from Line 4 to Line 1, the outputs may start to oscillate between 0 and 1 values.

The best way to wrap one's head around all of this is to consider how things occur across time by means of a waveform diagram (Fig.8.) Let's assume that we power up our SR latch at time t_0 with both S and R inputs in their inactive 0 states (Line 1 in the truth table). For reasons that will become obvious as we proceed, this means we don't know whether output Q will be a 0 or a 1 (whatever it is, QB will have the opposite value). We are showing such conditions as '?', meaning 'unknown,' in our waveform diagram (the 'X' character is also often used for this purpose).

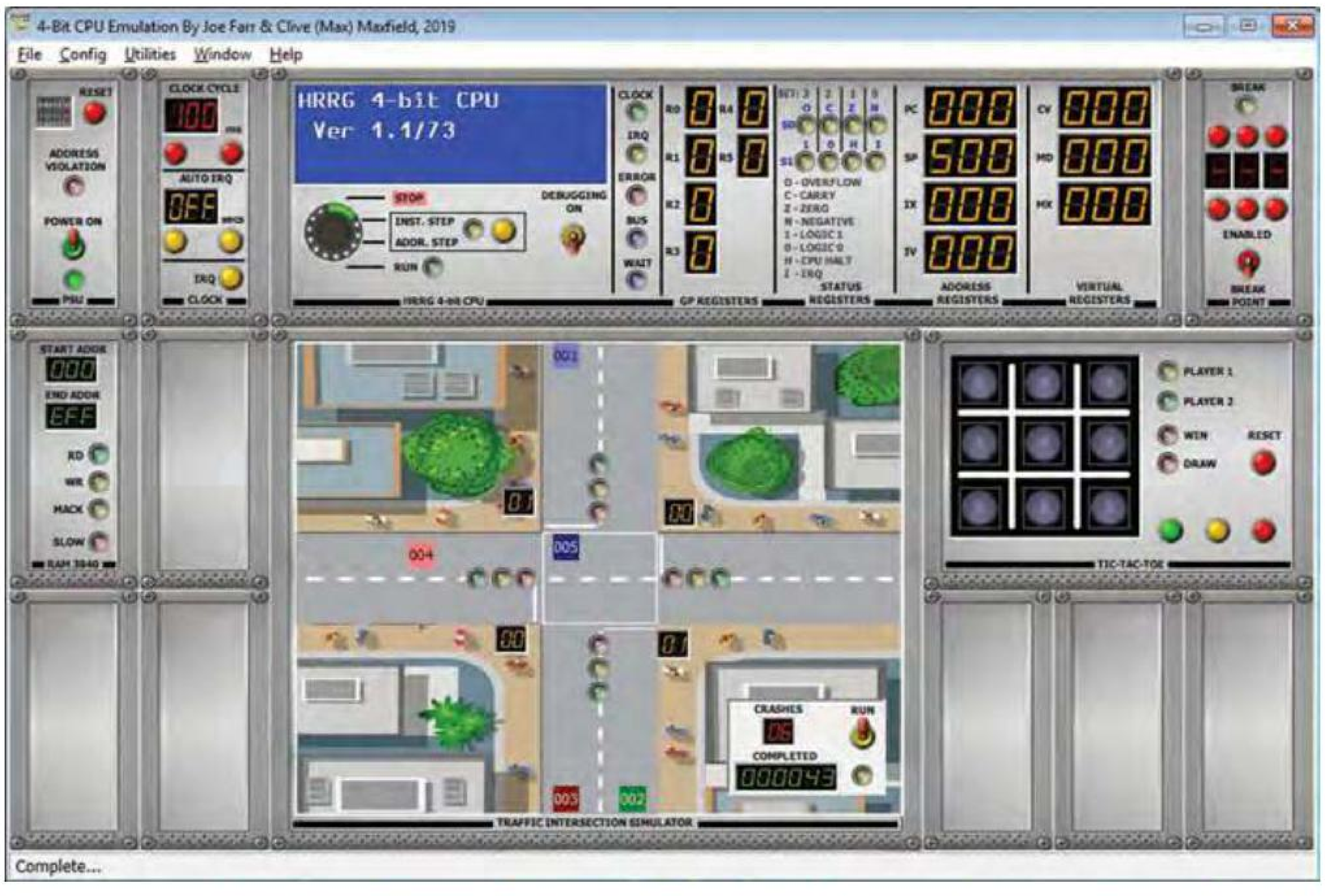


Fig.6. Virtual version of the 4-bit *HRRG Computer*.

Remember that if any input to a NOR gate is 1, then its output will be forced to 0; it's only when both inputs to a NOR gate are 0 that its output will be 1. Also remember that logic gates in the real world have propagation delays (the time it takes for them to react to a change on an input and modify their output), which we've shown as t_p in our waveform diagram.

In this example, at time t_1 we make our R input go to its active 1 state, thereby moving to Line 3 in the table, which will cause the Q output to transition to 0 after propagation delay t_p. This 0 on Q is fed back to the lower NOR gate (g2). Since this gate's S input is also 0, this means that the QB output will transition to 1 after a further propagation delay t_p. This 1 on QB is fed back to the upper NOR gate (g1).

Clever

Now, this is the clever bit, because when we return the R input to its 0 state at time t_2, thereby returning to Line 1 in the table, the 1 from the QB output fed back to the upper NOR gate continues to hold the output Q at 0. Thus, in this case, the latch remembers that R was the most recent input to be active.

At time t_3 we make our S input go to its active 1 state, thereby moving to Line 2 in the table, which will cause the QB output to transition to 0 after propagation delay t_p. This 0 on QB is fed back to the upper NOR gate g1. Since this gate's R input is also 0, this means that the Q output will transition to 1 after a further propagation delay t_p. This 1 on Q is fed back to the lower NOR gate g2.

Once again, this is the clever bit, because when we return the S input to its 0 state at time t_4, thereby returning to Line 1 in the table, the 1 from the Q output fed back to the lower NOR gate continues to hold the output QB at 0. Thus, in this case, the latch remembers that S was the most recent input to be active.

Now consider what happens at time t_5 when both S and R end up in their active 1 states (Line 4 in the table). In this case, the 1 on the R input forces the Q output to 0; similarly, the 1 on the S input forces the QB output to 0. At time t_6 we set both R and S inputs to 0, which moves us from Line 4 to Line 1 in the table.

This is where things get tricky. Since both the R and QB inputs to the upper NOR gate are currently 0, this will start the process of transitioning the Q output to 1. At the same time, since both the S and Q inputs to the lower NOR gate are currently 0, this will start the process of transitioning the QB output to 1.

After propagation delay t_p, both the Q and QB outputs will transition to 1. Now, the 1 on the Q output being fed back to the lower NOR gate will start the process of transitioning the QB output to 0. At the same time, the 1 on the QB output being fed back to the upper NOR gate will start the process of transitioning the Q output to 0.

After propagation delay t_p, both the Q and QB outputs will transition to 0… and round and round we go… with both the Q and QB outputs oscillating back and forth between 0 and 1. If everything were perfectly symmetrical and both halves of the SR latch were 100% identical, this oscillation could carry on until the end of time. In the real world, however, the transistors forming the NOR gates will have tiny differences, the wires linking the gates will have dissimilarities, and the loading on the Q and QB outputs will also have variations. As a result, the latch will eventually cease its oscillations and end up with Q being 0 or 1 and QB having the complementary value. The problem is that we don't know which way thing will end up, which is not the way we like things to be.

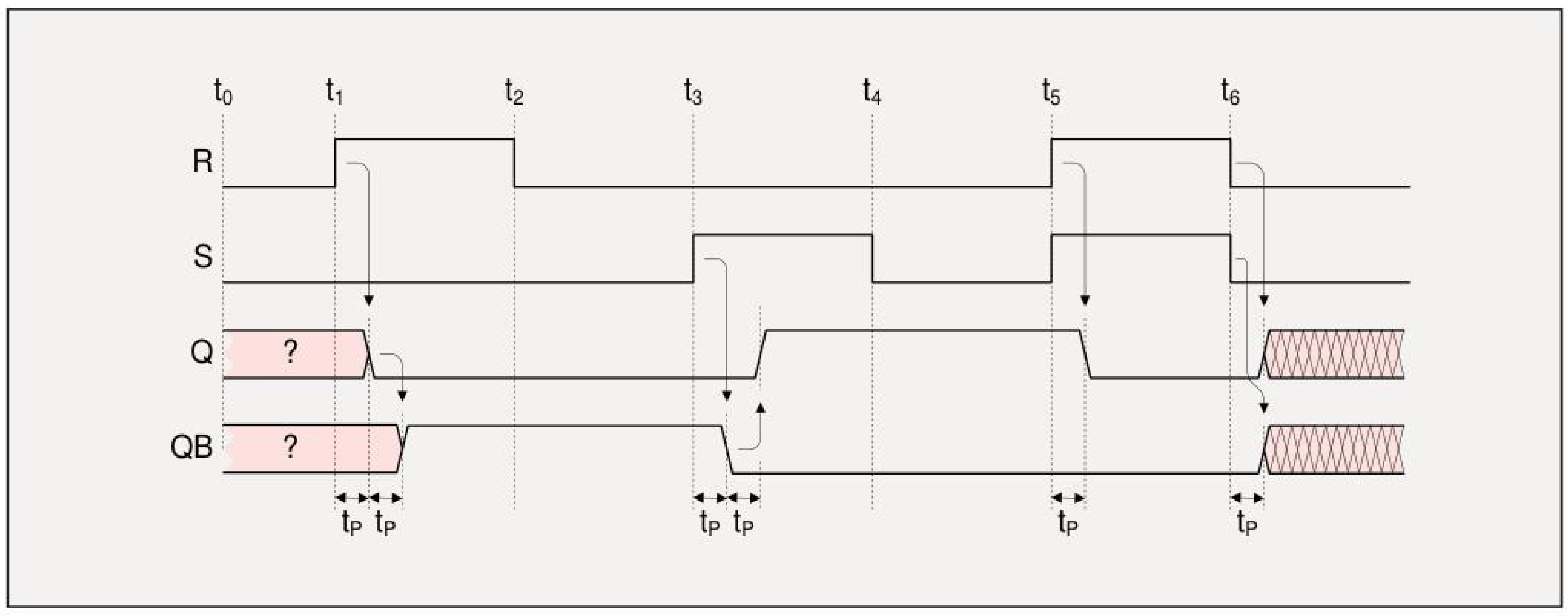


Fig.8. Waveform diagram for the SR Latch.

Ready, setup... hold

In addition to being interesting and useful in its own right, the asynchronous SR latch (or something similar) appears at the heart of more complex register elements, such as the commonly used synchronous D-type flip-flop. Unfortunately, in the same way that the SR latch can be coerced into entering an unstable oscillating state, so too can violating a flip-flop's setup or hold parameters causing it to enter a metastable condition, which is not considered to be a good thing.

In my next column, we will consider the causes of metastability and the ways in which we can mitigate against it. Until then, have a good one!

Cool bean Max Maxfield (Hawaiian shirt, on the right) is editor-in-chief at **EEWeb.com** – the go-to site for users of electronic design tools and askers of electronic questions.

Comments or questions? Email Max at: **max@CliveMaxfield.com**

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Make it with Micromite

Phil Boyce – hands on with the mighty PIC-powered, BASIC microcontroller

Part 7: Adding sound to a project

Many projects can benefit from the inclusion of simple audible notifications, so this month we will explore just how easy it is to incorporate sound into a Micromite-based project. To achieve this we will use a low-cost piezo sounder, along with MMBASIC's `PWM` (pulse-width modulation) command. With only these two elements, we will demonstrate how to generate simple tones, which when played at certain frequencies will allow musical notes to be created. By stringing various notes together we will show how to play some basic tunes.

For those of you who have built the *Electronic Dice*, next month we will modify the project to create a *Prediction Game*. This will incorporate some of this month's sound effect techniques, and it will use the console window (ie, TeraTerm Screen) as an output to display the score (and instructions) for our game.

Also this month, following a few email requests from readers, we will cover how to use the *Micromite Keyring Computer* (*MKC*) and *Development Module* (*DM*) with Apple's operating system, MacOS.

Piezo sounder selection

The are basically two types of piezo sounder available: those that require a DC voltage (these are typically marked with a '+' symbol, and generally make a 'fixed' sound at a certain frequency), and those that work with an AC signal, allowing the frequency to be varied. We will use the second type here because we will be changing the frequency (and hence the note) being generated.

Many AC piezo sounders are available, and you may well have one lying around that can be used. The simplest type looks like two flat metal discs stuck together with a lead attached to each disc. This type will be fine to use; however, a little more volume will come from a piezo sounder that is encapsulated in a plastic housing. The particular piezo sounder we recommend is one that has two 'pins' (rather than wires), and these allow us to easily plug it directly into the *MKC*/*DM*, or directly into a breadboard (see Fig 1).

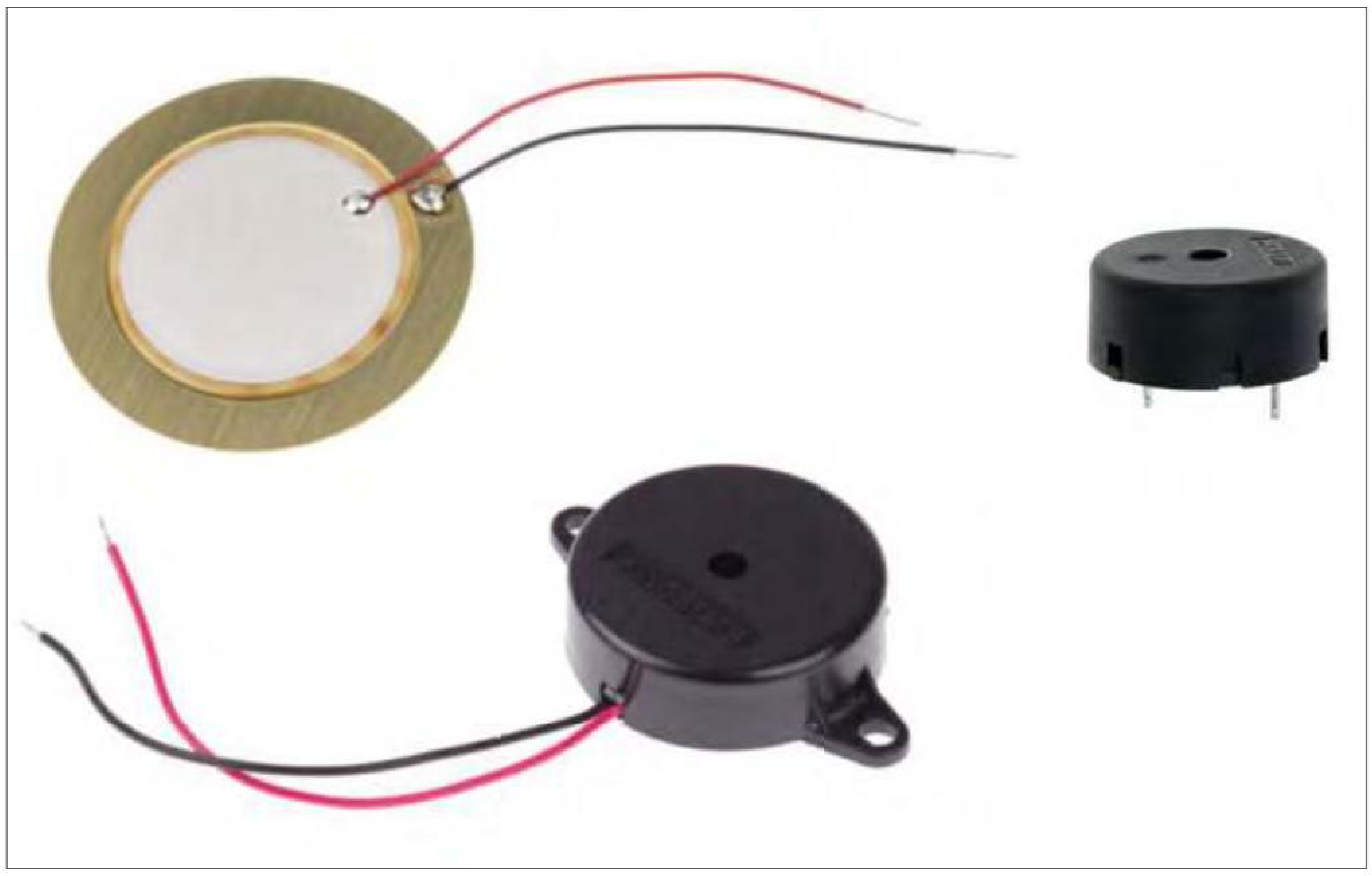


Fig.1. Any of these AC piezo sounders can be used. The one with pins (as opposed to wire connections) is easier to plug into the *MKC* and *DM* (or a breadboard).

Connecting the piezo to the Micromite

To drive an AC piezo sounder you do not actually need to apply an AC voltage. You can instead supply a rapidly toggling DC voltage (ie, a square wave), switching between on and off at one of the piezo's pins, while the other pin is connected to 0V. This may not result in the maximum possible volume from the piezo, but it is certainly sufficient to make useful sound with our Micromite.

So, go ahead and connect one lead of an AC piezo directly to Pin 26 on the *DM*. If you are using a **micromite.org** piezo then it can be oriented so that the other pin is inserted into Pin 22 (see Fig.2). We can then make Pin 22 simulate 0V by setting it to an output (ie, `SETPIN 22,DOUT`) and leaving it set low (which it will be by default). If you are using your own piezo then you can connect the other lead directly to 0V instead.

Now type the code in Listing 1 into your Micromite (comments are optional). `RUN` the code and you should hear a continuous tone from your piezo. Now press `Ctrl-C` to stop the program, and `EDIT` the code to change the value of variable `freq`. For the musically minded, if you double `freq` to `880` then you will shift up an octave to musical note A5. `RUN` the modified program and check that the note does indeed sound different.

The code (Listing 1) nicely demonstrates a square wave driving a piezo sounder to generate a tone. However, there is an MMBASIC command that can significantly simplify this code.

Questions? Please email Phil at:
contactus@micromite.org

Listing 1: How to generates a continuous square wave by repeatedly switching an I/O pin on and off

```
SETPIN 26,DOUT ` this pin will be used to rapidly toggle one side of the piezo between 3.3V and 0v
SETPIN 22,DOUT ` if using recommmended piezo, this pin will be used as the 0V supply to it
freq=440       ` set variable ‘freq’ with the frequency (Hz) of the note (440Hz = musical note A4)
T=1000/freq    ` T = time (in ms) for each complete square-wave cycle to generate required frquency
DO             ` loop to generate the required square-wave (50% duty: ie, half time On, half time Off)
  PIN(26)=1    ` apply 3.3V to piezo
  PAUSE T/2    ` for half the required cycle time
  PIN(26)=0    ` then apply 0V to piezo
  PAUSE T/2    ` for the other half of the cycle time
LOOP           ` go back and repeat
```

Micromite code

The code in this article is available for download from the *PE* website.

The PWM command

The program in Listing 1 will generate a tone that is not 100% accurate due to the time MMBASIC takes to process each line of code. Even though this processing time is very short, it has an impact on the overall sound because the frequency is slightly shifted. For general ‘beeps’ this frequency error is not an issue, but for playing musical tunes it does have an impact. However, the good news is that MMBASIC’s `PWM` command can overcome these timing issues because it accurately sets the output frequency on a dedicated PWM pin, and at any duty cycle between 0% and 100%. (Duty cycle simply refers to the percentage of time the PWM output pin is switched ‘on’ in one complete wave-cycle, so a value of 50 will give a perfect square wave.) On the *MKC*, there are two PWM channels (1 and 2), providing five PWM pins (named 1A, 1B, 1C, 2A, 2B); to keep things simple, we will only use one of these pins (PWM 2A) which outputs on Pin 26.

The PWM command we’ll use to make sound takes a simple form: `PWM 2,`*freq*`,`*duty* where *freq* is in Hz, and *duty* is a percentage (set to 50 to generate a square wave).

So, using the `PWM` command, Listing 1 now reduces to:

```
SETPIN 22,DOUT ` set 0V supply to piezo
PWM 2,440,50   ` Channel 2A (pin 26) 440Hz
```

Type `NEW` at the command prompt and enter the above two lines of code into the EDITor (comments optional). Now `RUN` the code. You will notice that the program ends after running the two lines of code (and returns you to the command prompt) – however, the sound continues to be heard. This is an example of a command that once triggered will continue until it is either changed (ie, a different frequency is set), or, it is stopped with the command: `PWM 2,STOP`

At the command prompt now type `PWM 2,880,50` (press Enter) and you will hear the sound change. Next type `PWM 2,STOP` to silence the piezo. Note that we did not need to use `SETPIN 26,DOUT` because the PWM command will automatically set the relevant pin as an output. Now that we have a very simple way to generate a tone, we can start to play with a few examples of making various sounds.

Simple beep

To play a simple beep we can take the single `PWM` command and place it into a `SUB` within a program. The `SUB` can then include a short delay before stopping the PWM output. Then, whenever we need a beep sound in a program we simply call the `SUB`. The example below beeps continually at one second intervals (100ms `BEEP` then 900ms silence). Return to the EDITor and modify the code to create the following program (once again, no need to enter the comments):

```
SETPIN 22,DOUT ` set 0V supply to piezo

` main program
  DO             ` create LOOP
    PAUSE 900    ` delay 900ms
    BEEP         ` call the BEEP subroutine
  LOOP           ` continue until stopped

` subroutines
SUB BEEP         ` sound piezo for 100ms
  PWM 2,440,50 ` Channel 2A (pin 26) 440Hz
  PAUSE 100      ` delay for 100ms
  PWM 2,STOP     ` switch PWM off
END SUB
```

Things to try

1. Change the pitch so it sounds more pleasing to your ears (ie, alter the `PWM` *freq* parameter)
2. Shorten the length of the tick sound, but keep the overall timing to one second (ie, reduce the 100ms delay and increase the 900ms delay)
3. Make it tick twice as fast (ie, the two `PAUSE` delays add up to 500ms instead of 1000ms)

Listing 2: A simple siren effect using the PWM command

```
SETPIN 22,DOUT                ` set 0V supply to piezo
DO
  FOR f = 400 to 2000 STEP 50  ` sweep through frequencies, start at 400Hz, then 450Hz... to 2kHz
    PWM 2,f,50                ` set the PWM output to frequency in variable f
    PAUSE 10                  ` short delay (10ms)
  NEXT f                      ` carry on up to 2kHz, then move to next line once 2kHz finished
  FOR f = 2000 to 400 STEP -50 ` now sweep down from 2kHz to 400Hz in 50Hz steps
    PWM 2,f,50
    PAUSE 10
  NEXT f                      ` when back down at 400Hz...
LOOP                          ` ...loop continually to create siren effect
```

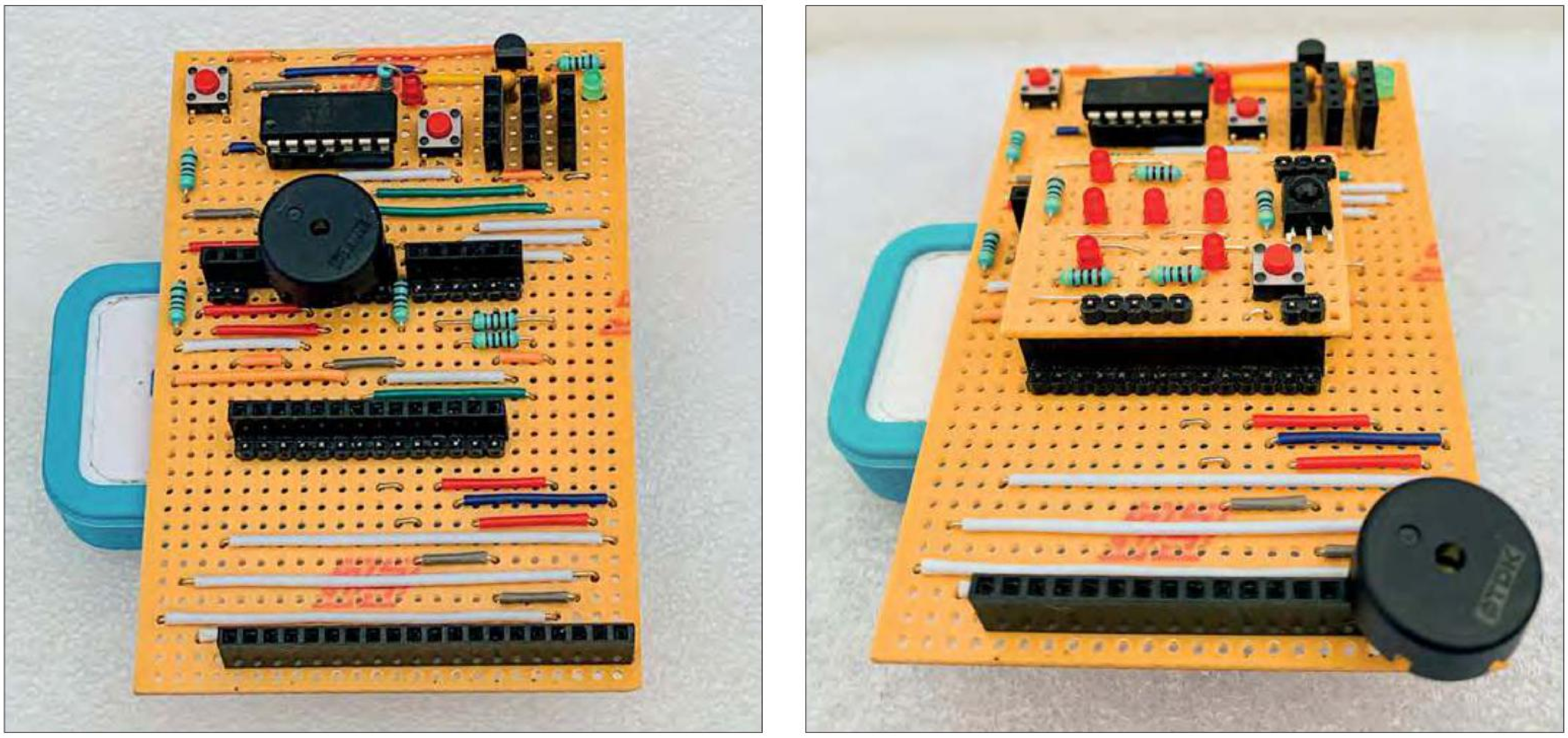


Fig 2. The recommend piezo can directly plug into the *MKC/DM* across Pin 22 and Pin 26 (above left). For next month's *Dice Predication* game we will need to also insert the *Electronic Dice* module, so connect the piezo to J12 (the 20-way connector). J12 is shown here as a socket with the piezo inserted directly into it (above right). If you have a row of pins for J12 instead, then simply plug the piezo into a breadboard and use a couple of jumper wires.

Siren effect

A sweeping effect can be created by rapidly increasing (or decreasing) the frequency. The code in Listing 2 repeatedly increases and then decreases the frequency to simulate a siren.

Note that when you stop the program with `Ctrl-C`, the sound will continue as explained above. Either type `PWM 2,STOP` (at the command prompt), or alternatively enter the EDITor (`F4`) and it will automatically stop the `PWM` output.

Things to explore

1. Change both `PAUSE 10` lines to `PAUSE 20` and hear the difference it makes. Play with other values between 1 and 50.
2. Experiment with different `STEP` values and hear the effect.
3. Alter the frequency sweep range to alter the siren tone.
4. Experiment with how high a frequency you can hear (don't upset nearby dogs!)

Playing tunes

Next, to play a tune, we not only need to know all the notes, but also the length of each note. With that information we can put everything into a program to play a tune. First, we'll form the foundation of a program and play a simple two-beep tune. This will make it easier to understand what happens when a tune is played – in effect, it is just a sequence of 'beeps'.

Generating musical notes

If you search online for 'musical note frequencies' then you will quickly find a list of frequencies that represent each musical note. The terminology used to name musical notes typically refers to the note itself (C, D, E, F, G, A or B) and an octave reference (typically a number between 1 and 7). A4, for example, is at a frequency of 440Hz. Going up an octave (to A5) effectively doubles this frequency to 880Hz – and that's about as far as my musical knowledge runs! However, this is sufficient information to start writing a program to play musical notes on the Micromite.

To begin our program we will define a list of notes, along with the relevant frequency for each note; and for this list we will introduce the `CONST` command. We have used variables in our programs many times now; for example, in the above siren-effect code we used variable `f` to represent the frequency value. We could use the same variable concept here to assign frequencies to each note variable (ie, `A4=440`, `A5=880`), but a much better method for defining our list of note frequencies is what is called a 'constant' (since the frequency for each note is fixed and does not vary). To define a constant we simply use the `CONST` command – best demonstrated with an example. Start a new program and enter the following three lines of code:

```
SETPIN 22,DOUT  ' set 0V supply to piezo
CONST C4=262,D4=294,E4=330,F4=349,G4=392,A4=440,B4=494
CONST C5=523,D5=587,E5=659,F5=698,G5=784,A5=880,B5=988
```

Now `RUN` the program (nothing will appear to happen) and you will be returned to the command prompt. At the command prompt, type C5=10 and see what happens. The point here is that we have given C5 a value of 523 (at the time we declare C5 as a constant), and hence this value cannot be changed anywhere – even at the command prompt. So, providing all the notes are each given the correct frequency value, then we know that any musical note will sound correct.

A point worth explaining here is that multiple constants can be defined by separating each with a comma. So in the above, the first `CONST` line simply defines the seven notes in the fourth octave but only uses a single `CONST` command. This helps keep things tidy and easy to read.

To hear a note played, type its name into the `PWM` command. Run the program, then at the command prompt enter: `PWM 2,G4,50` (remember that the sound will continue until changed or stopped).

Now type: `PWM 2,C5,50` and a different musical note (`C5`) will play. (Enter the EDITor (`F4`) to silence the piezo). We now have a mechanism for playing any musical note that we have defined (ie, named) in our `CONST` list. However, to play a tune we also need to take into account note duration to avoid having to manually stop the `PWM` output.

Defining note duration

Note duration can be defined by a value such that '1' represents a 'whole' note, '2' represents a half-note (ie, half the duration), '4' represents a quarter-note, '8' represents

Listing 3: Code to play multiple musical tunes – each tune has Note and Duration information grouped in the DATA lines

```
‘setup
SETPIN 22,DOUT                     ` set 0V supply to piezo
CONST C4=262,D4=294,E4=330,F4=349,G4=392,A4=440,B4=494
CONST C5=523,D5=587,E5=659,F5=698,G5=784,A5=880,B5=988
CONST pp=0                         ` represents a silent note
Tempo=1.0                          ` increase to speed up, decrease to slow down

` Tune data
  ` Two pieces of data per note, the note name and note duration: Note, Duration
  ` For Duration: 1=whole note, 2=half note, 4=quarter note, 8=eighth...
Tune1:
  DATA C4,2, C4,2 G4,2, G4,2, A4,2, A4,2, G4,1
  DATA F4,2, F4,2 E4,2, E4,2, D4,2, D4,2, C4,1
  DATA G4,2, G4,2 F4,2, F4,2, E4,2, E4,2, D4,1
  DATA G4,2, G4,2 F4,2, F4,2, E4,2, E4,2, D4,1
  DATA C4,2, C4,2 G4,2, G4,2, A4,2, A4,2, G4,1
  DATA F4,2, F4,2 E4,2, E4,2, D4,2, D4,2, C4,1, PP,999 ` end-of-tune marker (ie, Duration = 999)

Tune2:
  DATA G4,4, G4,4, A4,2, G4,2, C5,2, B4,1, PP,32
  DATA G4,4, G4,4, A4,2, G4,2, D5,2, C5,1, PP,32
  DATA G4,4, G4,4, G5,2, E5,2, C5,2, B4,2, A4,1, PP,16
  DATA F5,4, F5,4, E5,2, C5,2, D5,2, C5,1, PP,999

` main program
DO
  RESTORE Tune1                    ` point MMBASIC to Tune1 DATA
    PlayTune                       ` call SUB to play the tune contained in the DATA
    PAUSE 1000                     ` have a gap before next tune
  RESTORE Tune2                    ` point to Tune 2
    PlayTune                       ` Play the tune
    PAUSE 1000                     ` and another gap before next tune
LOOP                               ` continually play the two tunes....

` subroutines
SUB PlayTune
  DO
    READ Note, Duration            ` read two bits of note-data, load into variables: Note and Duration
    IF Duration=999 THEN EXIT DO   ` check to see if ‘end-of-tune’ marker. If so then exit DO/LOOP
    IF Note>20 THEN PWM 2,Note,50  ` check if a note. If so, set PWM pin 26 at frequency in Note
    PAUSE 1000/(Duration * Tempo)  ` leave note playing for required time
    PWM 2,STOP                     ` now stop the PWM output
    PAUSE 10/Tempo                 ` add a small pause before next note
  LOOP                             ` continue with next note...
END SUB
```

an eighth and so on. This concept is based on the US note-naming convention that is easier to relate to (when it comes to coding) than the English naming convention of crotchets, quavers and minims. If this seems confusing, just think of 1 being a ‘long’ note, 2 being half that time, 4 shorter still, 8, 16, 32, 64 getting progressively shorter.

Assuming a whole note is one second (ie, 1000ms), then the actual time (in ms) that the note sounds for is 1000/duration.

For example, a note duration of 4 (representing a quarter-note) needs to sound for (1000/4) ms = 250ms (ie, a quarter of a second).

So each musical note can now comprise of two pieces of meaningful data: a note name and a duration. For example, `C5,4` which in code, would be represented as:

```
PWM 2,C5,50     ` play note C5 on pin 26
PAUSE 1000/4    ` allow note to play for 250ms
PWM 2,STOP      ` ... before switching off PWM
```

Tempo

We can make a very simple change to the above `PAUSE` line of code allowing us to use a variable (let’s call it `Tempo`) to adjust the speed of playback. If a value of 1 for Tempo represents ‘normal’ speed then the `PAUSE` formula becomes:

```
PAUSE 1000/(Duration * Tempo)
```

Setting `Tempo` to 2 means our note duration of 4 changes from 250ms to (1000/(4 × 2)) = 125ms (twice as fast). For completeness, setting `Tempo` to 0.5 means our note duration of 4 becomes (1000/(4 × 0.5)) = 500ms (twice as slow – half the speed). With this formula we can also use a `Tempo` value such as 1.2 to speed a tune up just a little.

Time to pause

We are almost at the point where we have all the building blocks in place – but there are two more things we need to cover regarding playing tunes. We currently have the ability to play a named note for a set duration, and can also speed the tune up, or slow it down with the variable `Tempo`. However, notes have a natural pause between them. It can be likened to reading a sentence – there is a very brief pause between each word. This is relatively easy to implement since all we need to do is simply add a 10ms delay between each note with the command `PAUSE 10`. And bringing our `Tempo` variable into the equation, it simply becomes: `PAUSE 10/Tempo`

The final thing we need in place is the ability to have a variable-length silent note. One way to achieve this is to define a note (let's use a constant named `pp` to represent a silent note) and give it a frequency value of 0 (so we can add `CONST pp=0` to our list of notes). Then we can use it just like any other note and pass a duration value to represent the length of the silence. However, there is one issue with this, the `PWM` command needs a frequency value of at least `20` otherwise an error is generated. Unfortunately, if we use `20` as the frequency defined for `pp`, then clicks will be heard rather than the required silence, so we need another solution which actually turns out to be really simple. Let's consider the previous example of playing note `C5`:

```
PWM 2,C5,50    ' play note C5 on pin 26
```

Let's modify this slightly by loading the required note into a variable, which we will call `Note`. The code then becomes:

```
Note=C5         ' load variable 'Note' with the value
                ' stored in Constant C5 (ie, 523)
PWM 2,Note,50   ' set pin 26 frequency to value
                ' in Note (ie, 523Hz)
```

The above would still give an error with the `PWM` command if we were to use `Note=pp`. To prevent this error, all we need to do is to check if the value in `Note` is greater than 20; hence the code becomes:

```
Note=C5
IF Note>20 THEN PWM 2,Note,50
```

If we now play `Note pp` (instead of `C5`) then the `PWM` command won't be executed and hence no error will occur. However, any `Note` with a frequency value greater than `20` will be output on pin 26 as a square wave.

Bringing it all together

Now we have worked through the concepts, we can create a `SUB` (`PlayTune`) to play a musical note defined by the data in two variables, `Note` and `Duration`. To play a tune we simply pass pairs of note data to `PlayTune`, as seen in the `main program` section in the code below.

```
'setup
SETPIN 22,DOUT
'Note Names and Frequencies (Hz)
CONST C4=262,D4=294,E4=330,F4=349,G4=392,A4=440,B4=494
CONST C5=523,D5=587,E5=659,F5=698,G5=784,A5=880,B5=988
CONST pp=0
Tempo=1.0

' main program
Note=E4:Duration= 8:PlayTune
Note=pp:Duration=16:PlayTune
Note=C4:Duration= 2:PlayTune

' subroutines
SUB PlayTune
  IF Note>20 THEN PWM 2,Note,50
  PAUSE 1000/(Duration * Tempo)
  PWM 2,STOP
  PAUSE 10/Tempo
END SUB
```

When you `RUN` the program you should hear a two-tone beep. We will be using this tune in next month's *Dice Game* as a notification of an incorrect guess.

Hopefully, you fully understand what each line of code is doing; and do remember that more details of each command can be found in the *Micromite User Manual*.

Playing longer tunes

The above code is fine for tunes comprising just a few notes, but it becomes a bit tedious to type in a long tune due to the 'long' list of `Note` and Duration variables that would need to be entered. We will therefore modify the program to make it easier to enter a long tune by using the commands `DATA`, `READ`, and `RESTORE`.

The three lines of `Note` and `Duration` values in the main program above can be put into a `DATA` command as follows:

```
DATA E4,8, pp,16, C4,2 : PlayTune
```

(The spaces between the pairs of data are purely for clarity – they are not required and can be left out).

We can then read this data by using the `READ` command in our `SUB PlayTune`, as shown here:

```
SUB PlayTune
  DO
    READ Note, Duration
    IF Note>20 THEN PWM 2,Note,50
    PAUSE 1000/(Duration * Tempo)
    PWM 2,STOP
    PAUSE 10/Tempo
  LOOP
END SUB
```

Since we have a `DO`/`LOOP` in our `SUB`, it will eventually generate an error because the `READ` line of code will run out of available `DATA` at the end of the tune. You can see this by RUNning the program; even though you hear the tune, you will also see the error message: `No DATA to read`.

To overcome this we can add a simple 'end-of-tune' marker in our `DATA`. The easiest way to do this is to add a dummy pair of data at the very end of the tune with an otherwise unused value (such as `999`) for the `Duration`. Then in our `SUB` we just need to check the value of `Duration` after each `READ`, and simply exit the `SUB` if `Duration` equals `999`. If this sounds complex, then don't worry. All we need to do is add a single `IF...THEN` line of code to the `SUB`; along with the additional dummy pair of data in the `DATA` line. See below:

```
DATA E4,8, pp,16, C4,2, pp,999 : PlayTune
SUB PlayTune
  DO
    READ Note, Duration
    IF Duration=999 THEN EXIT DO
    IF Note>20 THEN PWM 2,Note,50
    PAUSE 1000/(Duration * Tempo)
    PWM 2,STOP
    PAUSE 10/Tempo
  LOOP
END SUB
```

If you haven't already done so, replace the three '`Note`' lines currently in the 'main program' with the single `DATA` line shown above; and also modify the `SUB PlayTune` to include the `DO`, `LOOP`, `READ` and `IF/THEN` lines, as shown above.

Now `RUN` the program and all should work as before. Admittedly, this is not a long (or exciting) tune, but we now have the ability to play a longer tune by simply adding more notes in the form of a pair of values to the `DATA` lines.

We will now demonstrate how to continually play two simple (hopefully recognisable) tunes with just a slight change to our program. We will also use the `RESTORE` command to point to the correct tune `DATA`. Let's begin by looking at the overall program in Listing 3.

Here we have two tunes, each with its own set of tune `DATA` (ending in `pp, 999` as explained previously), and each set of tune `DATA` has been given a label: `Tune1` and `Tune2`. These labels will be used as pointers so that the correct tune is played (ie, the correct set of `DATA` is read). It would be sensible to use the name of the tune as the label as it makes it easier to follow which tune is being played – but for now we have not done so – we want you to discover what the tunes are by hearing them!

In the main program, the `RESTORE` command simply informs MMBASIC where to start reading `DATA` from when the next `READ` command is encountered. So `RESTORE Tune1` simply instructs MMBASIC to use the `DATA` for the first tune. The `SUB PlayTune` is then called, which works through the note data pairs until the end-of-tune marker is encountered. Then there is a one-second gap before the second tune is played. It is hopefully self-explanatory how the program continues from here to play the second tune. The `DO`/`LOOP` in the main program simply plays both tunes continually. Now run the program and confirm that you can indeed recognise the two simple tunes.

Add your own music!

If you can read music, then see if you can add your own tune `DATA` to the above – call it `Tune3`. Simply add as many `DATA` lines as needed, ensuring that each note has a pair of `DATA` values (ie, a `Note` name, and a `Duration`). Also, don't forget at the end of the tune to add an additional pair of dummy data to signify the end-of-tune marker (ie, with the `Duration` set to `999`). If you need notes from any other octaves, then simply add more CONSTants at the start of the program with the names and frequencies that are readily available online.

Next month

In the next article we will make a *Prediction Game* based on the *Electronic Dice* from last month, which will incorporate our new sound techniques. Plus, we will make an *MKC Clock* with a cute mini IPS display and a high-accuracy real-time clock module.

Micromite and Apple Mac

So far in this series, instructions have been provided for connecting a Micromite to a Windows PC. The TeraTerm application was downloaded from the Internet and configured to be used as the 'console' application. TeraTerm then provides the required user interface via the computer's keyboard and screen.

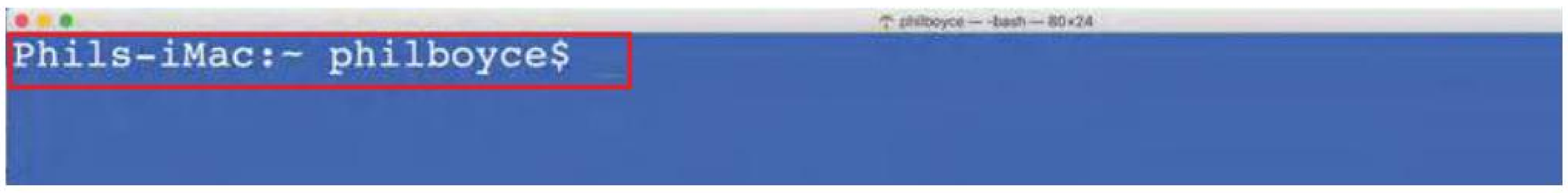
We will now explain how to connect the *MKC/DM* to an Apple Mac. It is a little easier than the Windows PC setup because no drivers or additional applications need be downloaded – everything, including the Terminal application is supplied from within the Apple Mac operating system, MacOS.

Note that these instructions are provided for Mac OS X version 10.7 or later – I don't have an old enough Mac to test pre-10.7. If you manage to use these instructions with an 'older' Mac then your feedback would be welcome and I'll share tips.

Overview

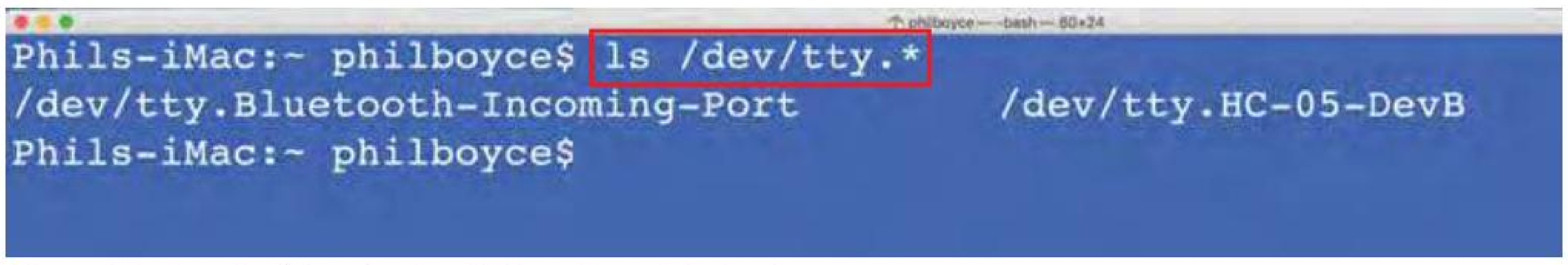
A summary of the steps involved is as follows:

- Discover the device name MacOS assigns to the *MKC/DM*
- Connect to the *MKC/DM*
- Test the connection
- Configure display (and behaviour) settings.



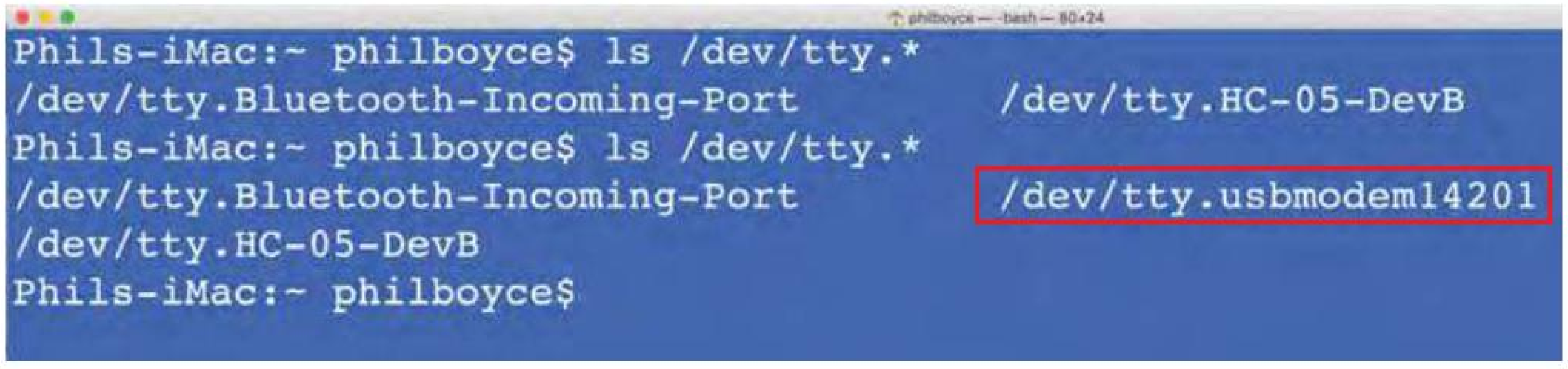
```
Phils-iMac:~ philboyce$
```

Fig.1. Terminal screen at launch (you may well see different screen/font colours).



```
Phils-iMac:~ philboyce$ ls /dev/tty.*
/dev/tty.Bluetooth-Incoming-Port        /dev/tty.HC-05-DevB
Phils-iMac:~ philboyce$
```

Fig 2. Typing ls /dev/tty.* will list all serial devices.



```
Phils-iMac:~ philboyce$ ls /dev/tty.*
/dev/tty.Bluetooth-Incoming-Port        /dev/tty.HC-05-DevB
Phils-iMac:~ philboyce$ ls /dev/tty.*
/dev/tty.Bluetooth-Incoming-Port        /dev/tty.usbmodem14201
/dev/tty.HC-05-DevB
Phils-iMac:~ philboyce$
```

Fig 3. MKC/DM device-name showing up as additional item in list.

Full disclosure – I'm no expert with MacOS, but these instructions will at least get your *MKC/DM* connected so that you can explore MMBASIC and follow all the *Make it with Micromite* articles. No doubt there will be many ways to improve usability; for example, by adding a desktop icon to launch directly into the user interface. Let's use the power of mass readership; please forward to me any MacOS suggestions so that they can be shared.

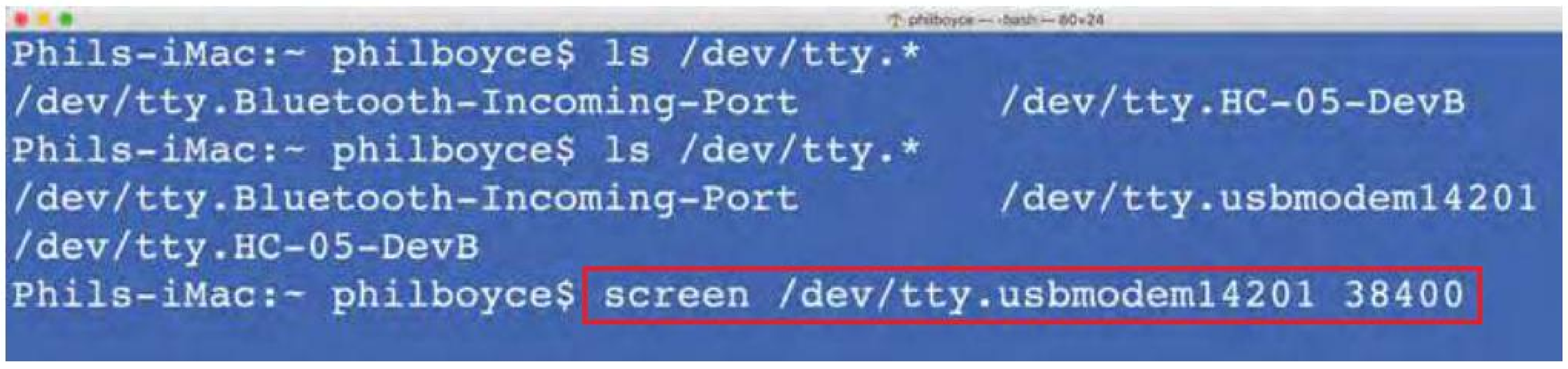
Discover the device name that MacOS assigns to the MKC/DM

Step 1 – To start the built-in Terminal application, go to the Applications folder and then Utilities, there you will find the application 'Terminal'. Simply double-click on the Terminal icon to start it and you will see something similar to Fig.1

Step 2 – With the *MKC/DM* **not** plugged in, type: `ls /dev/tty.*` (This will list all the serial devices connected to the Mac – see Fig.2.)

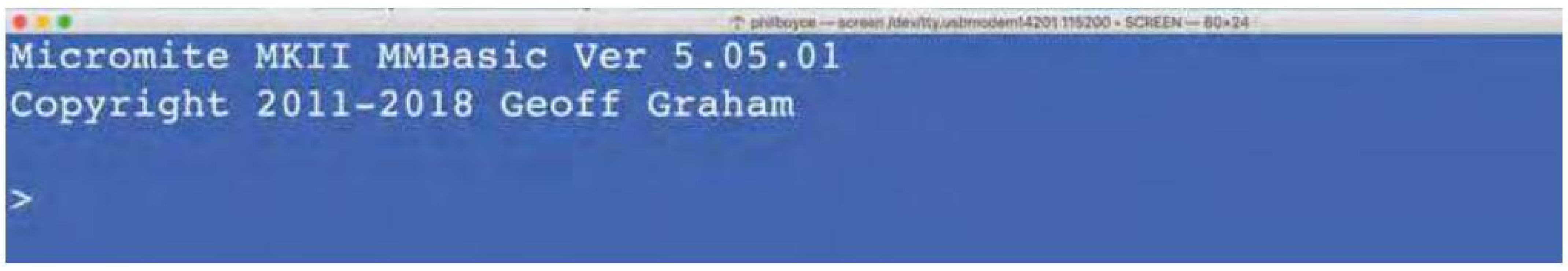
Step 3 – Now plug the *MKC/DM* into a USB port. Hit the UP cursor key, which will bring the search command back (`ls /dev/tty.*`) and hit the Enter key. You should get the exact same list as before, but this time with a new serial device. It will look something like: `/dev/tty.usbmodemXXXXX` (where `XXXXX` is some value). See Fig.3.

This is the device name we need (on my Mac it is: `/dev/tty.usbmodem14201`).


philboyce — -bash — 80×24

```
Phils-iMac:~ philboyce$ ls /dev/tty.*
/dev/tty.Bluetooth-Incoming-Port        /dev/tty.HC-05-DevB
Phils-iMac:~ philboyce$ ls /dev/tty.*
/dev/tty.Bluetooth-Incoming-Port        /dev/tty.usbmodem14201
/dev/tty.HC-05-DevB
Phils-iMac:~ philboyce$ screen /dev/tty.usbmodem14201 38400
```

Fig 4. Launching Terminal's screen console: *MKC/DM* device-name and 38400 baud rate.


philboyce — screen /dev/tty.usbmodem14201 115200 • SCREEN — 80×24

```
Micromite MKII MMBasic Ver 5.05.01
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>
```
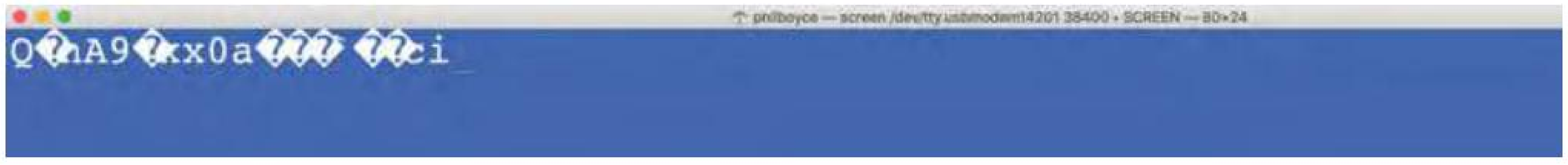
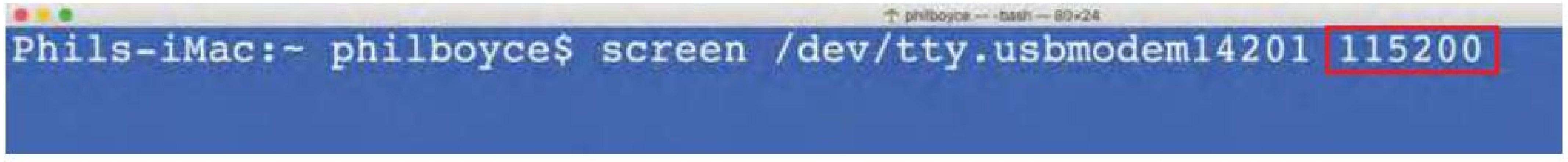

Fig 5. If all is well, you will see the Micromite 'Welcome message'.


philboyce — screen /dev/tty.usbmodem14201 38400 • SCREEN — 80×24

```
Q�hA9�xx0a��� ��ci
```

Fig 6. This garbled screen indicates the incorrect baud rate was selected.


philboyce — -bash — 80×24

```
Phils-iMac:~ philboyce$ screen /dev/tty.usbmodem14201 115200
```

Fig 7. If baud rate is incorrect, re-connect at 115200.

Note the full device name – you'll need it in the next step.

Connect to the MKC/DM

Step 4 – Terminal's Screen feature provides the console that we will use to communicate with the Micromite (ie, the equivalent of TeraTerm on a Windows PC). To launch Screen, simply type the following into the Terminal screen already open: `screen /dev/tty.usbmodemXXXXX 38400` (replace `XXXXX` with your device name value). The number `38400` at the end is the baud rate (speed) for the serial connection to the Micromite – see Fig.4.

I recommend that the baud rate connection is speeded up to 115200, as explained in an earlier article. However, for this to work, the Micromite will need `OPTION BAUDRATE 115200` set. Put simply, whatever the Micromite is set to (38400 by default), the number needs to be the same in the (Fig.4) Screen command.

Test the connection

Step 5 – To test the connection, press the Reset button on the Development Module (top left button). If you see the Micromite's 'welcome message' (Fig.5) then you have the correct baud rate selected in Step 4.

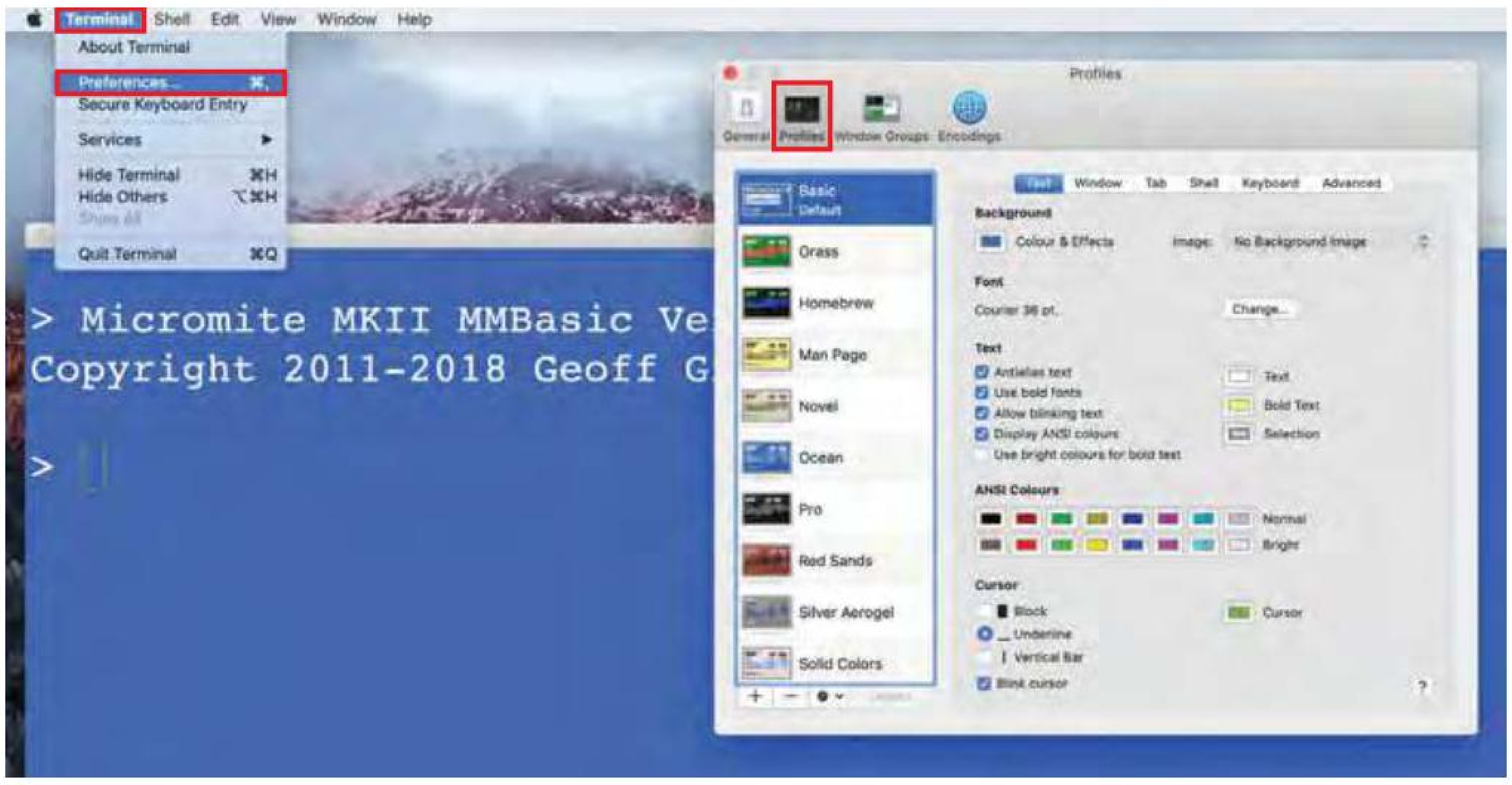
However, if you see random looking characters/graphics (Fig.6) then chances are you have used an incorrect baud rate value in Step 4. In this case, close down the Screen window (red circle 'x' in top left corner), briefly unplug the MKC/DM from the Mac, re-insert it back into the USB port, and then relaunch Terminal and repeat Step 4 with 115200 instead of 38400 (you can use the UP cursor key to repeat the last thing typed, and then the BackSpace key to delete the '38400' – this just saves a bit of time!). See Fig.7

When you see the Micromite 'welcome message' then the connection is good and we can move on to configuring some display settings.

Configure display (and behaviour) settings

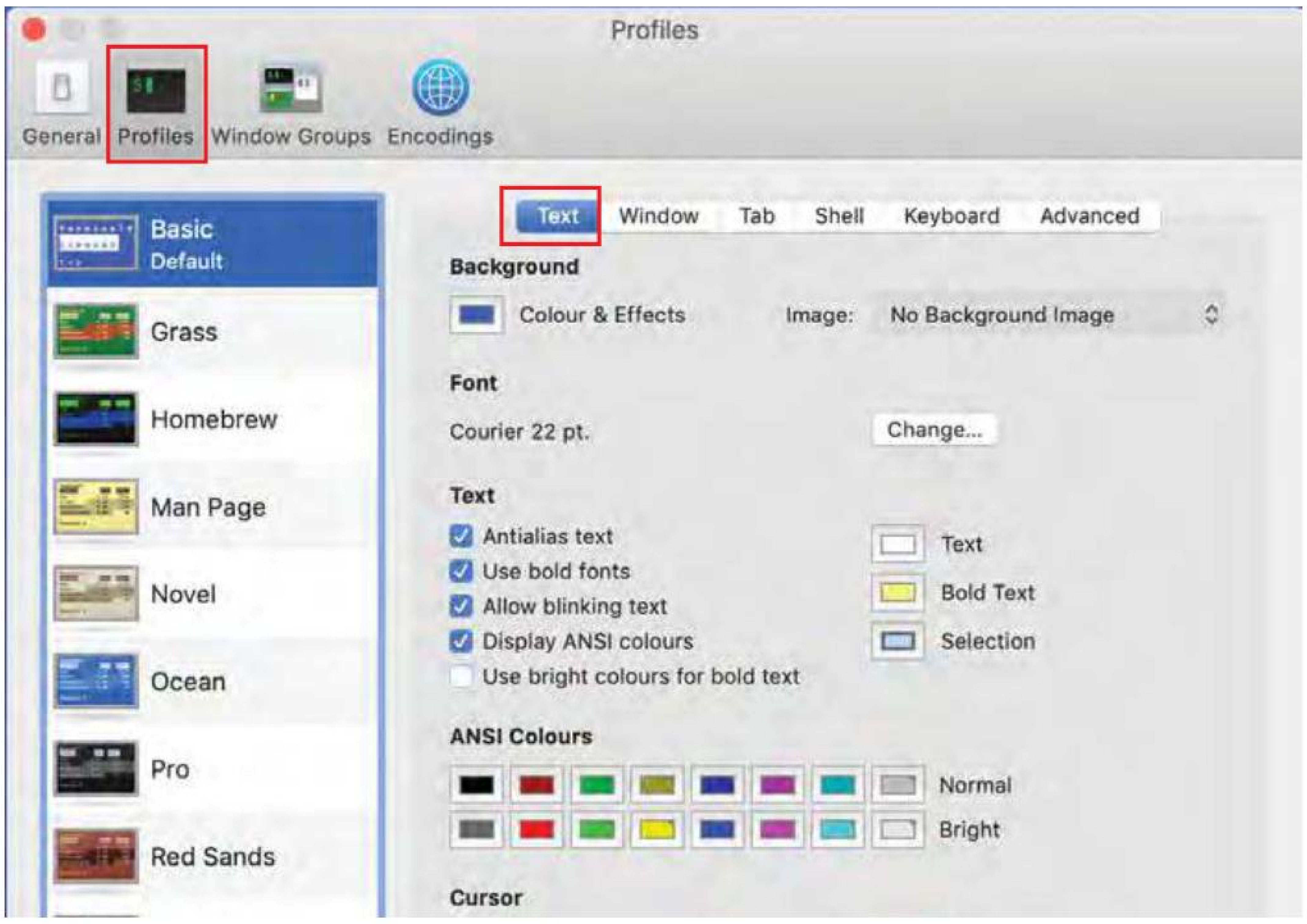
All of the settings are made in the Terminal/Preferences/Profiles menu option – See Fig.8.

Step 6 – Colour and font: I like using the Micromite with a console display that has white characters on a blue background. When it comes to font choice, make sure you use a non-proportional font such as Courier, as this helps to line up columns properly. The colours and font settings can be changed in the Preferences/Profiles 'Text' tab. See the screenshot (Fig.9) for the settings that I


Terminal
Shell
Edit
View
Window
Help
About Terminal
Preferences… ⌘,
Secure Keyboard Entry
Services ▶
Hide Terminal ⌘H
Hide Others ⌥⌘H
Show All
Quit Terminal ⌘Q
Profiles
General
Profiles
Window Groups
Encodings
Basic
Default
Grass
Homebrew
Man Page
Novel
Ocean
Pro
Red Sands
Silver Aerogel
Solid Colors
Text
Window
Tab
Shell
Keyboard
Advanced

```
> Micromite MKII MMBasic Ve
Copyright 2011-2018 Geoff G

>
```

Fig 8. To change Terminal settings, select 'Preferences', and then 'Profiles'.


Profiles
General
Profiles
Window Groups
Encodings
Basic
Default
Grass
Homebrew
Man Page
Novel
Ocean
Pro
Red Sands
Text
Window
Tab
Shell
Keyboard
Advanced
Change…
Normal
Bright
Cursor

Background

Colour & Effects   Image: No Background Image

Font

Courier 22 pt.

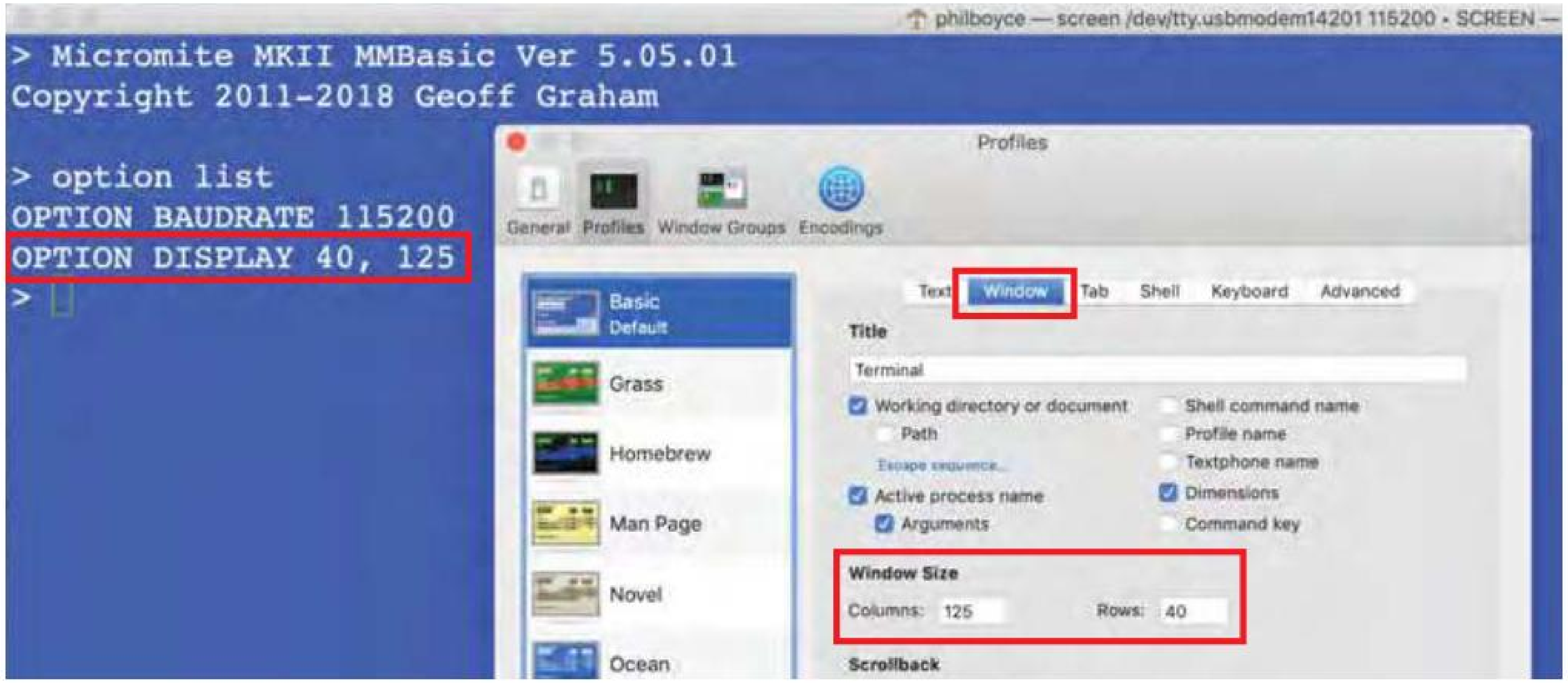
Text

☑ Antialias text
☑ Use bold fonts
☑ Allow blinking text
☑ Display ANSI colours
☐ Use bright colours for bold text

Text
Bold Text
Selection

ANSI Colours

Fig 9. Select the 'Text' tab to change Colours, and Font style.



philboyce — screen /dev/tty.usbmodem14201 115200 • SCREEN —
Profiles
General
Profiles
Window Groups
Encodings
Basic
Default
Grass
Homebrew
Man Page
Novel
Ocean
Text
Window
Tab
Shell
Keyboard
Advanced
Scrollback

```
> Micromite MKII MMBasic Ver 5.05.01
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> option list
OPTION BAUDRATE 115200
OPTION DISPLAY 40, 125
> 
```

Title: Terminal

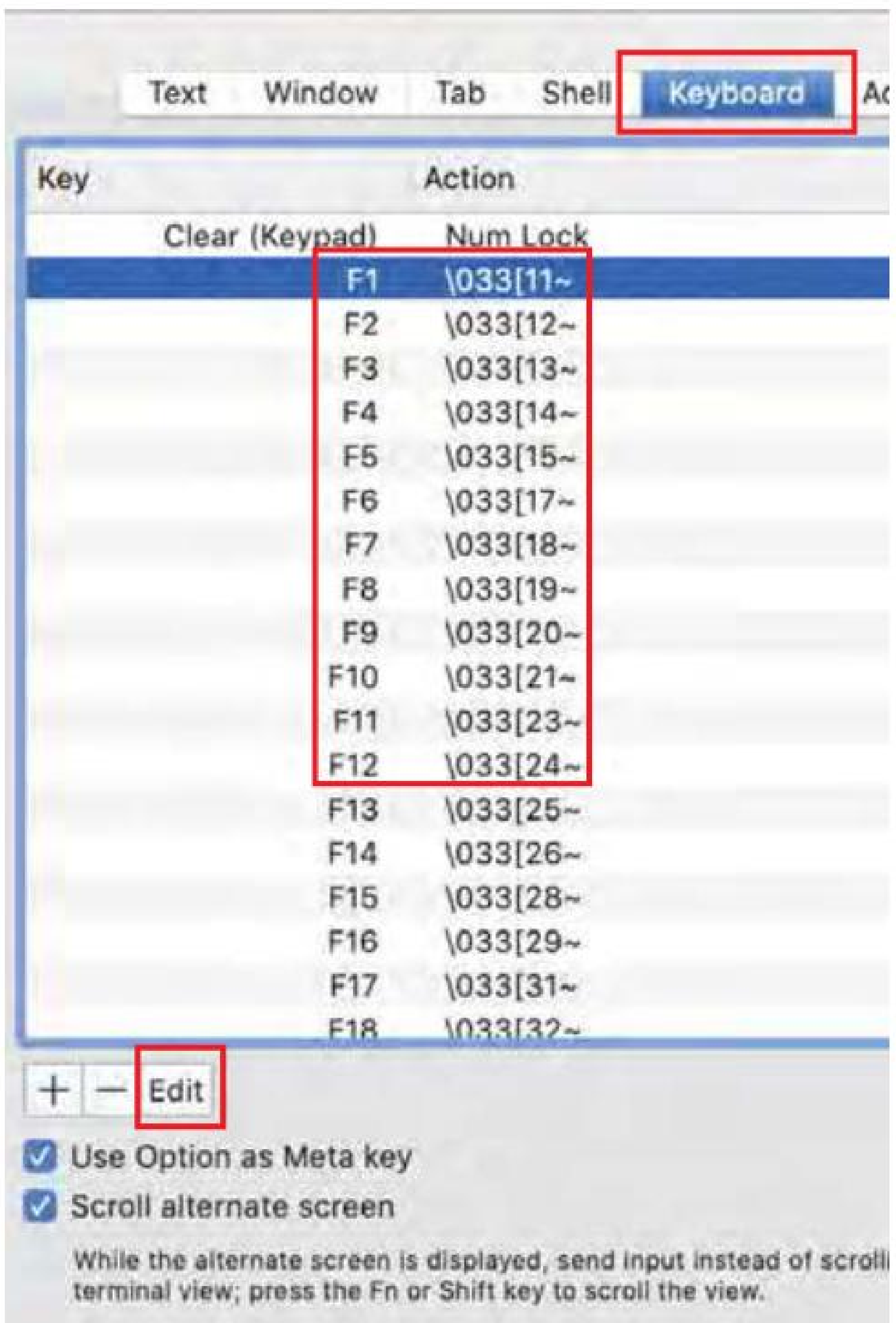
☑ Working directory or document
☐ Path
Escape sequence...
☑ Active process name
☑ Arguments
☐ Shell command name
☐ Profile name
☐ Textphone name
☑ Dimensions
☐ Command key

Window Size
Columns: 125
Rows: 40

Fig 10. Select the 'Window' tab to change the Window size. It needs to match the Micromite OPTION DISPLAY values.

have; colour is a matter of personal taste, so just select what works best for you. Note that as you make changes you will see the effect in real time in the Screen window, which can certainly help you choose colours.

Step 7 – Window size: now that you have a connection to the Micromite, type `OPTION LIST` at the command prompt (you may need to press `Ctlr-C` first to stop any AutoRunning program). If you have made `OPTION` changes from default values then these will be displayed. To make a useable console size I recommend setting `OPTION DISPLAY 40,125` on the Micromite. You only need to make this setting once (if it isn't already set) because `OPTION` choices are stored in Flash memory. Then, under Terminal's Preferences/Profiles Window tab make the Window Size the same (note Columns and Rows order are swapped around) as shown in the screenshot in Fig.10. This ensures that the Micromite's built-in EDITor fits on the screen properly, so it's an important step to perform.



Text
Window
Tab
Shell
Keyboard
Ac
+
−
Edit

Key	Action
Clear (Keypad)	Num Lock
F1	\033[11~
F2	\033[12~
F3	\033[13~
F4	\033[14~
F5	\033[15~
F6	\033[17~
F7	\033[18~
F8	\033[19~
F9	\033[20~
F10	\033[21~
F11	\033[23~
F12	\033[24~
F13	\033[25~
F14	\033[26~
F15	\033[28~
F16	\033[29~
F17	\033[31~
F18	\033[32~

☑ Use Option as Meta key
☑ Scroll alternate screen
While the alternate screen is displayed, send input instead of scrolli terminal view; press the Fn or Shift key to scroll the view.

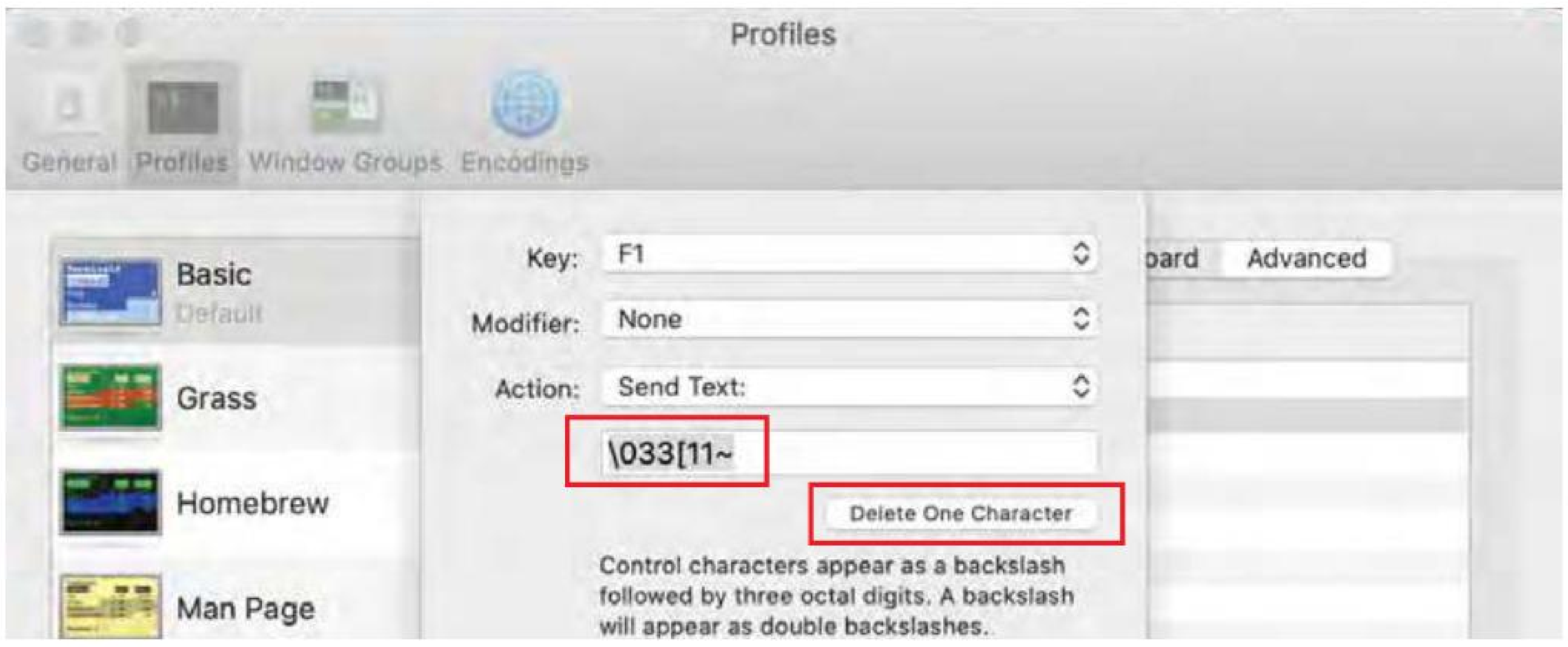
Fig 11. Select the 'Keyboard' tab to set up the Function keys.

Step 8 – Function key settings: MMBASIC uses several of the Function keys F1-F12; especially for the built-in Editor. For the Function keys to work correctly, the Keyboard menu needs to have the Function key settings as shown in Fig.11). In particular, look at the Action for those Function keys highlighted. For example, F1 needs to have action: `\033[11~`

If you need to make a change, then click on the relevant Function key in the list (and it will become highlighted), and then select the Edit button. This will display a pop-up window as shown in Fig.12. The Action can then be edited accordingly. Note: you must use the 'Delete One Character' button to delete characters (rather than the Backspace or Delete keys on the keyboard). Once you have entered the correct information, simply click OK. You should then see the modified Action in the list. Ensure F1 through to F12 all match the Actions shown in the screenshot in Fig.11.

Step 9 – Advanced settings: To ensure that other aspects (such as the Delete key) work as required, check that your Advanced menu settings match those as shown in Fig.13.

That should be enough of a guide to get your Mac connected to the Micromite. As always, any issues – drop me an email and I will try and help you out.



Profiles
General
Profiles
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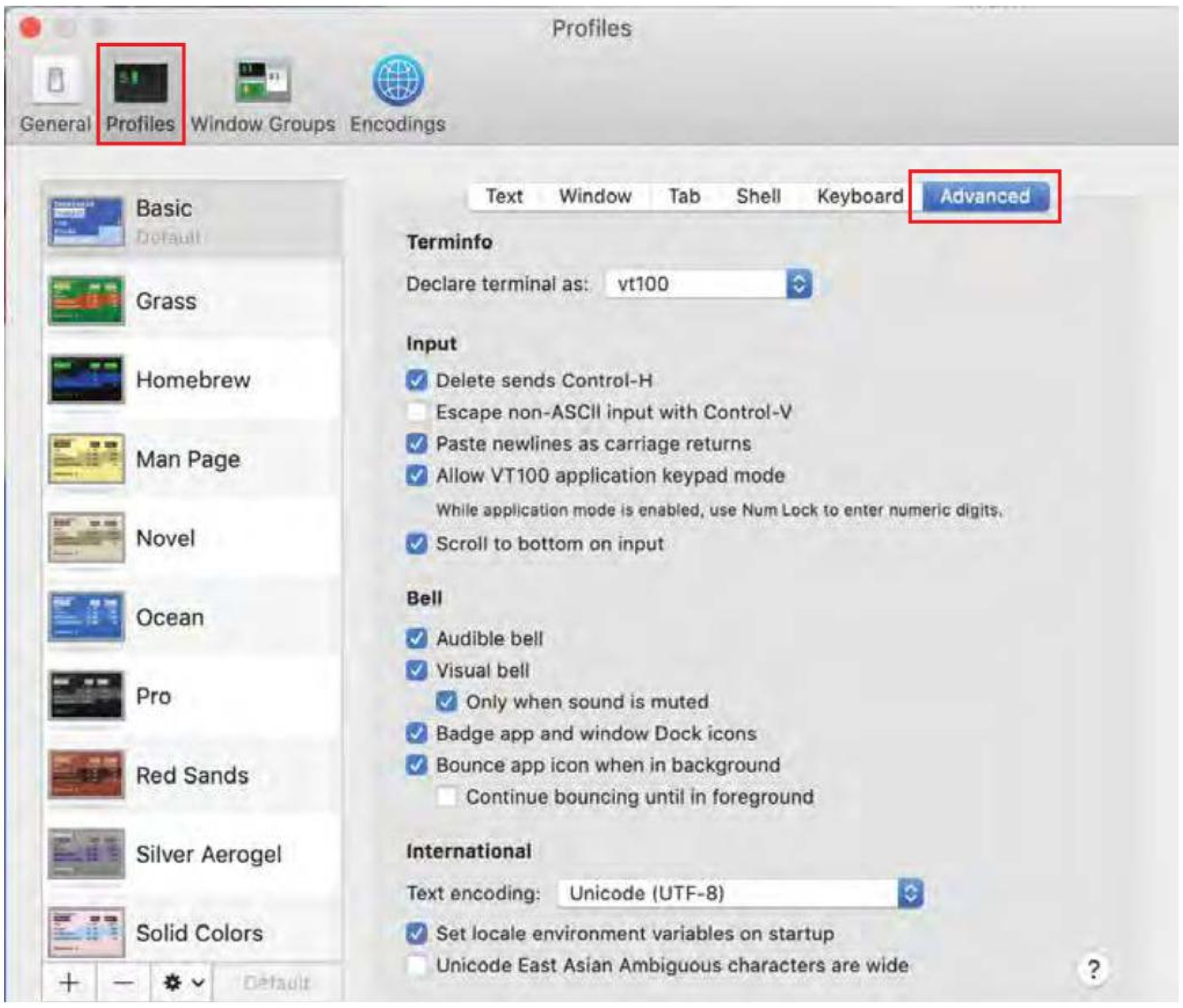
oard
Advanced
Delete One Character

Key: F1
Modifier: None
Action: Send Text:
\033[11~

Control characters appear as a backslash followed by three octal digits. A backslash will appear as double backslashes.

Fig 12. Ensure you Edit the Action data in the pop-up window.



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Default
Text
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Keyboard
Advanced
?

Terminfo
Declare terminal as: vt100

Input
☑ Delete sends Control-H
☐ Escape non-ASCII input with Control-V
☑ Paste newlines as carriage returns
☑ Allow VT100 application keypad mode
While application mode is enabled, use Num Lock to enter numeric digits.
☑ Scroll to bottom on input

Bell
☑ Audible bell
☑ Visual bell
☑ Only when sound is muted
☑ Badge app and window Dock icons
☑ Bounce app icon when in background
☐ Continue bouncing until in foreground

International
Text encoding: Unicode (UTF-8)
☑ Set locale environment variables on startup
☐ Unicode East Asian Ambiguous characters are wide

Fig 13. Select the 'Advanced' tab and set everything as shown here.

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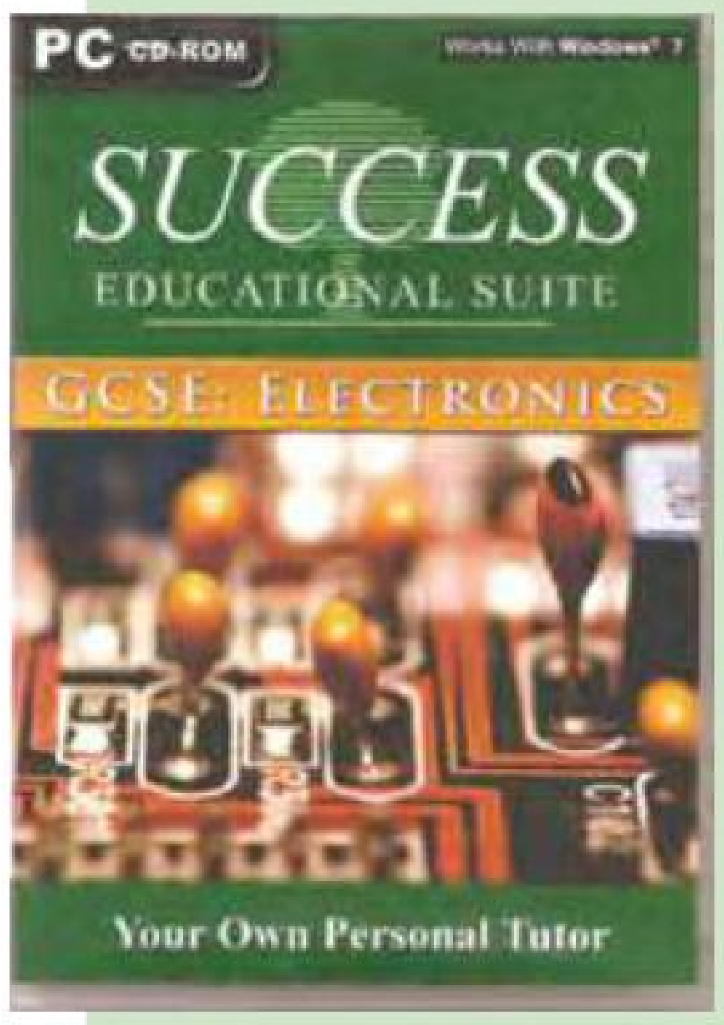
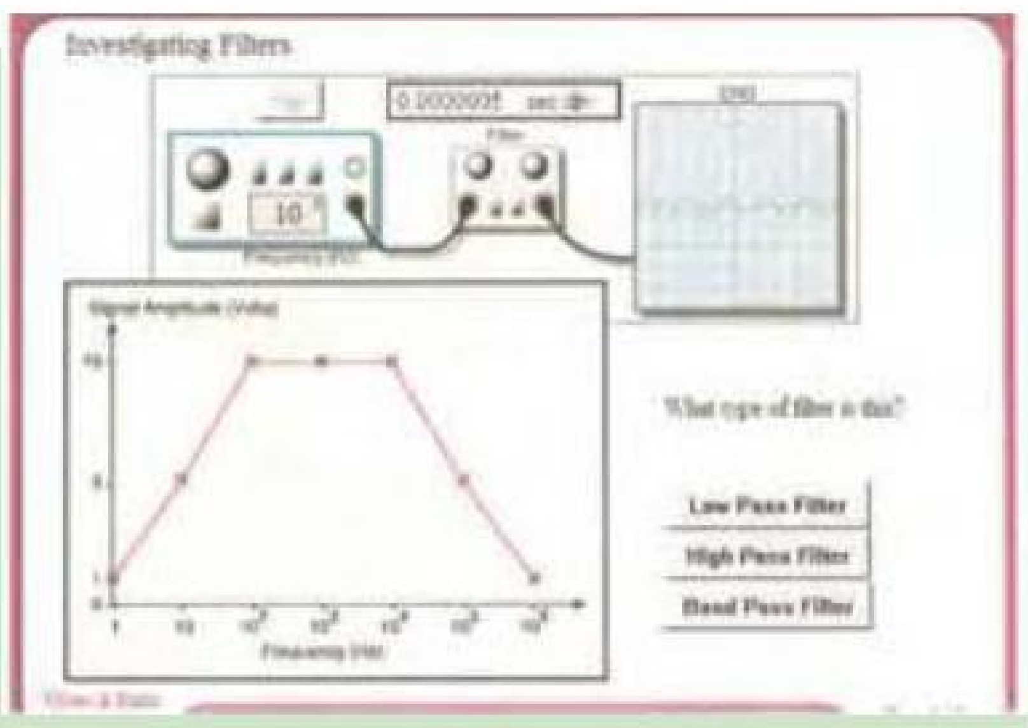
GCSE ELECTRONICS





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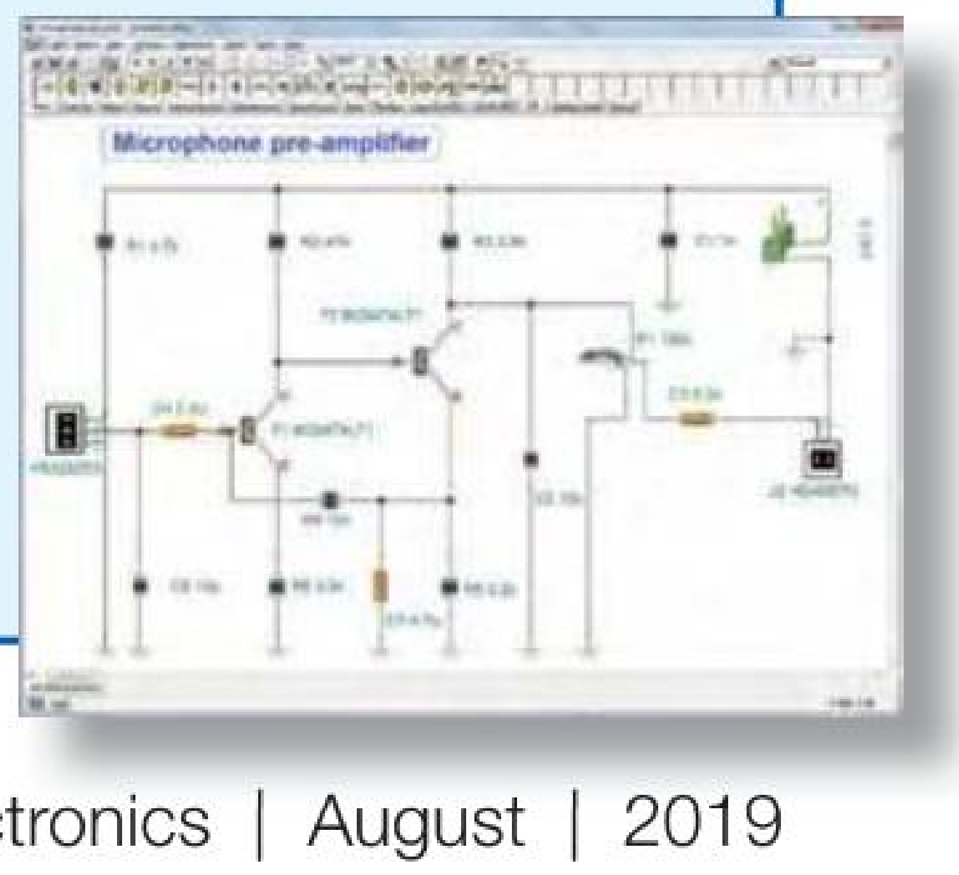

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SOFTWARE

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(Formerly PICtutor)

Assembly for PICmicro microcontrollers V7.0 (previously known as PICtutor) by John Becker contains a complete course in programming the PIC16F84, 16F88 and 16F877a PICmicro microcontroller from Arizona Microchip. It starts with fundamental concepts and extends up to complex programs including watchdog timers, interrupts and sleep modes.

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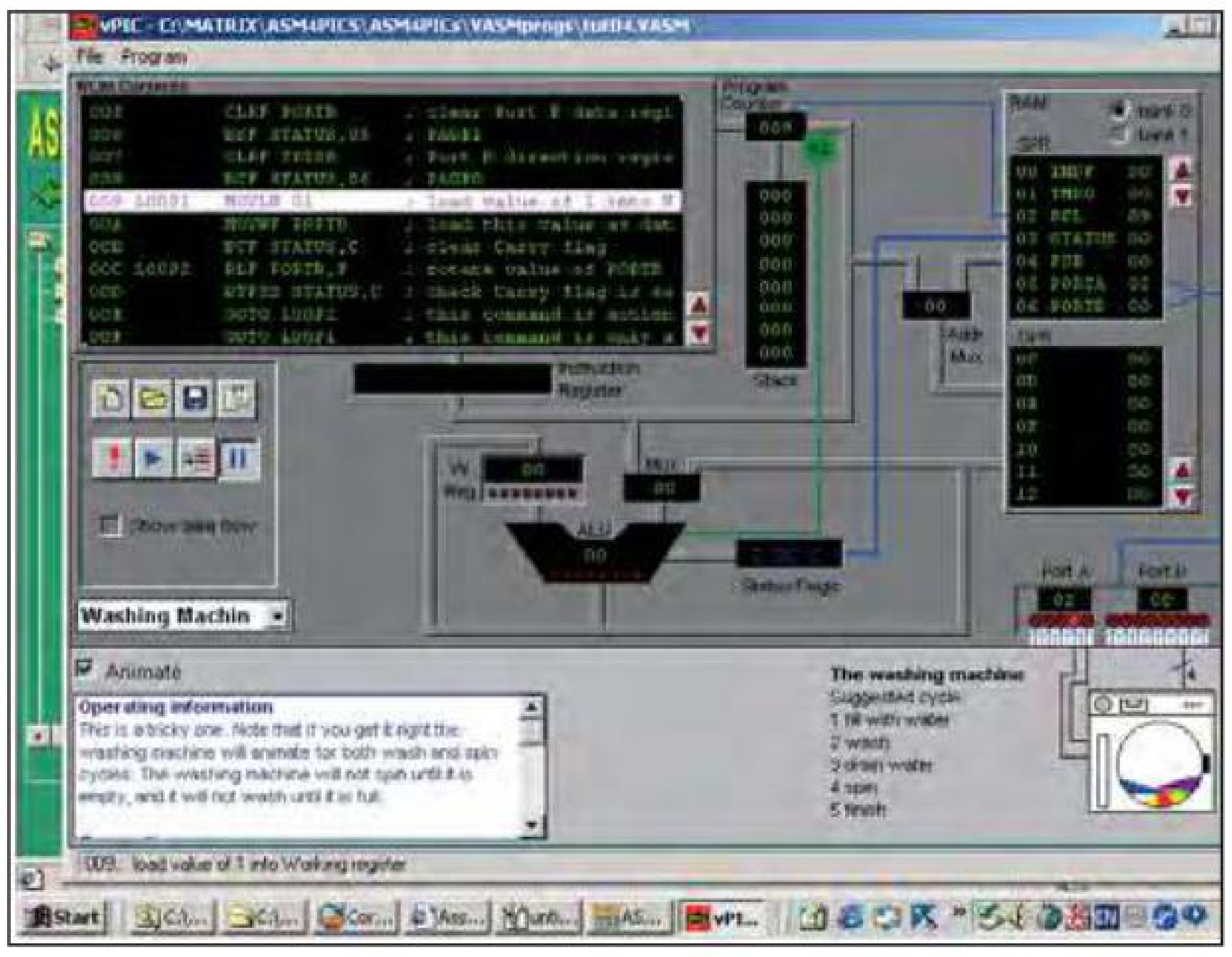

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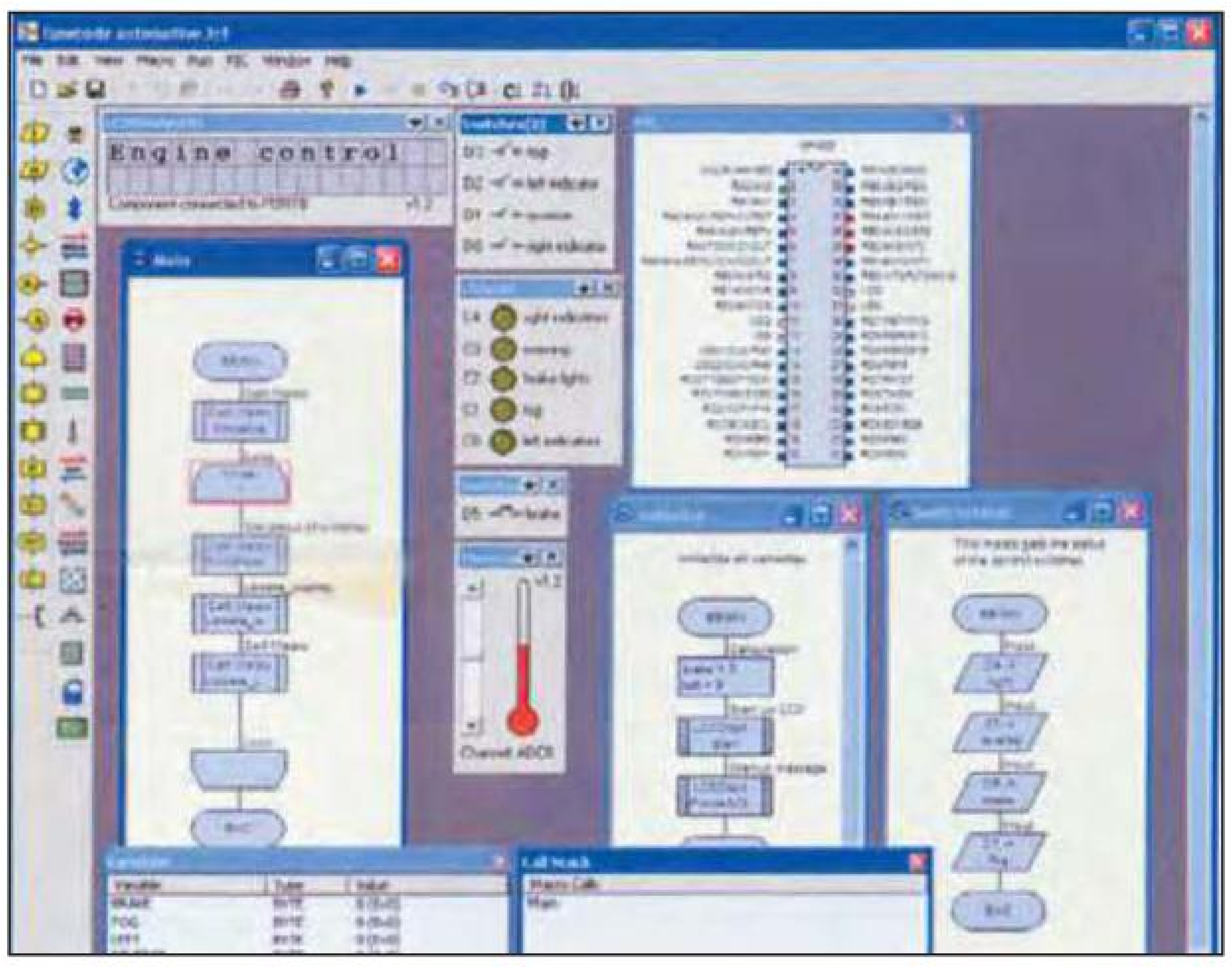

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This *Teach-In* series of articles was originally published in *EPE* in 2008 and, following demand from readers, has been collected together in the *Electronics Teach-In 2* CD-ROM.

The series is aimed at those using PIC microcontrollers for the first time. Each part of the series includes breadboard layouts to aid understanding and a simple programmer project is provided.

Also included are 29 *PIC N' Mix* articles, also republished from *EPE*. These provide a host of practical programming and interfacing information, mainly for those that have already got to grips with using PIC microcontrollers. An extra four part beginners guide to using the C programing language for PIC microcontrollers is also included.

The CD-ROM also contains all of the software for the *Teach-In 2* series and *PIC N' Mix* articles, plus a range of items from Microchip – the manufacturers of the PIC microcontrollers. The material has been compiled by Wimborne Publishing Ltd. with the assistance of Microchip Technology Inc.

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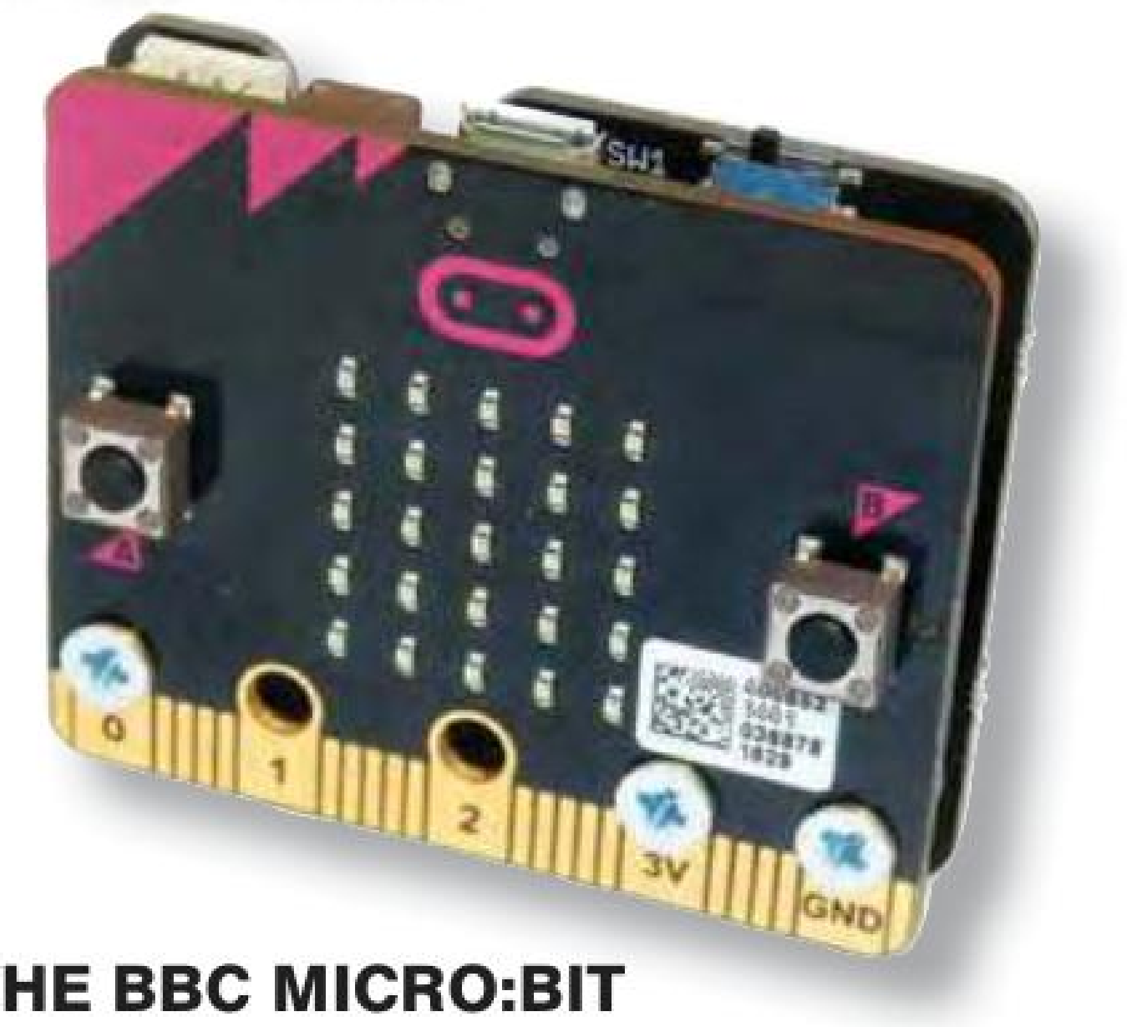


IN FULL COLOUR
For Beginners of Any Age
Python Coding on the BBC micro:bit
Jim Gatenby

PYTHON CODING ON THE BBC MICRO:BIT

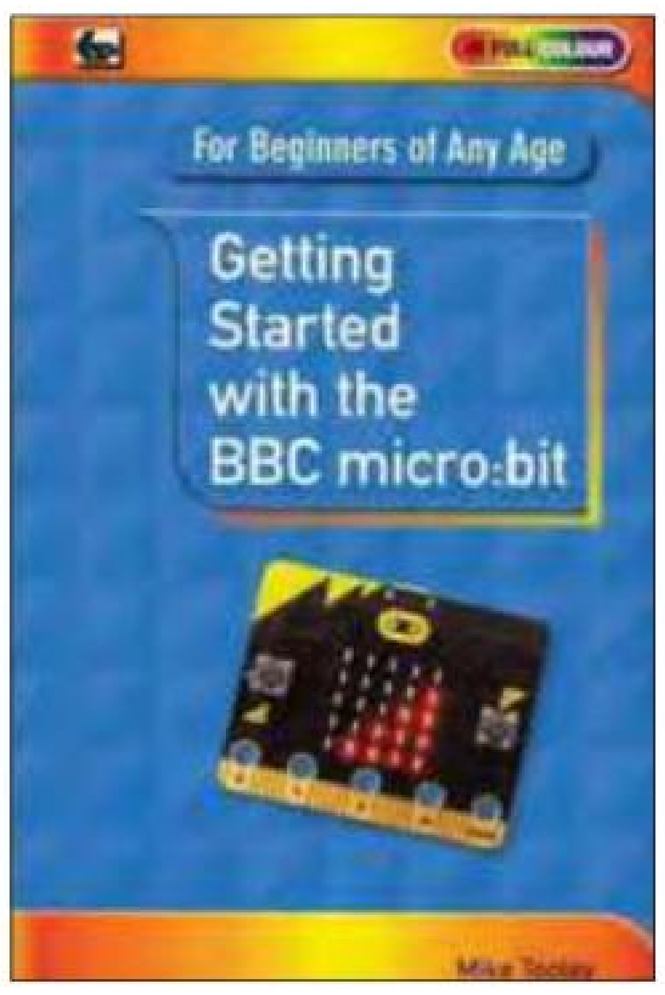
Jim Gatenby

Python is the leading programming language, easy to learn and widely used by professional programmers. This book uses MicroPython, a version of Python adapted for the BBC Micro:bit.

Among the many topics covered are: main features of the BBC micro:bit including a simulation in a web browser screen; various levels of programming languages; Mu Editor for writing, saving and retrieving programs, with sample programs and practice exercises; REPL, an interactive program for quickly testing lines of code; scrolling messages, creating and animating images on the micro:bit's LEDs; playing and creating music, sounds and synthesized speech; using the on-board accelerometer to detect movement of the micro:bit on three axes; glossary of computing terms.

This book is written using plain English, avoids technical jargon wherever possible and covers many of the coding instructions and methods which are common to most programming languages. It should be helpful to beginners of any age, whether planning a career in computing or writing code as an enjoyable hobby.

118 Pages **Order code PYTH MBIT** £7.99



GETTING STARTED WITH THE BBC MICRO:BIT

Mike Tooley

Not just an educational resource for teaching youngsters coding, the BBC micro:bit is a tiny low cost, low-profile ARM-based single-board computer. The board measures 43mm × 52mm but despite its diminutive footprint it has all the features of a fully fledged microcontroller together with a simple LED matrix display, two buttons, an accelerometer and a magnetometer.

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No previous coding experience is assumed, making this book ideal for complete beginners as well as those with some previous knowledge. Self-test questions are provided at the end of each chapter, together with answers at the end of the book. So whatever your starting point, this book will take you further along the road to developing and coding your own real-world applications.

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ARDUINO

Teach-In 2016

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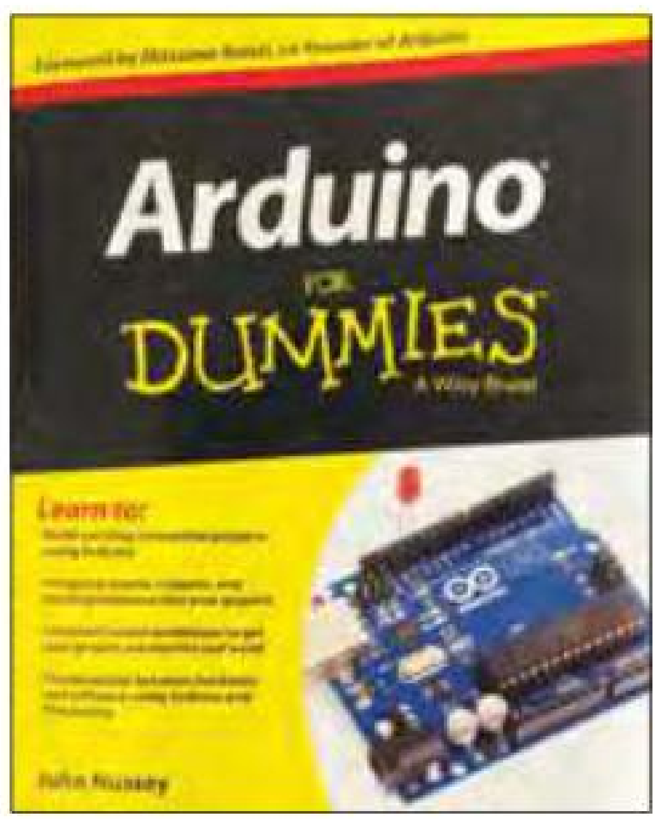

ARDUINO FOR DUMMIES
John Nussey

Arduino is no ordinary circuit board. Whether you're an artist, a designer, a programmer, or a hobbyist, Arduino lets you learn about and play with electronics. You'll discover how to build a variety of circuits that can sense or control real-world objects, prototype your own product, and even create interactive artwork. This handy guide is exactly what you need to build your own Arduino project – what you make is up to you!

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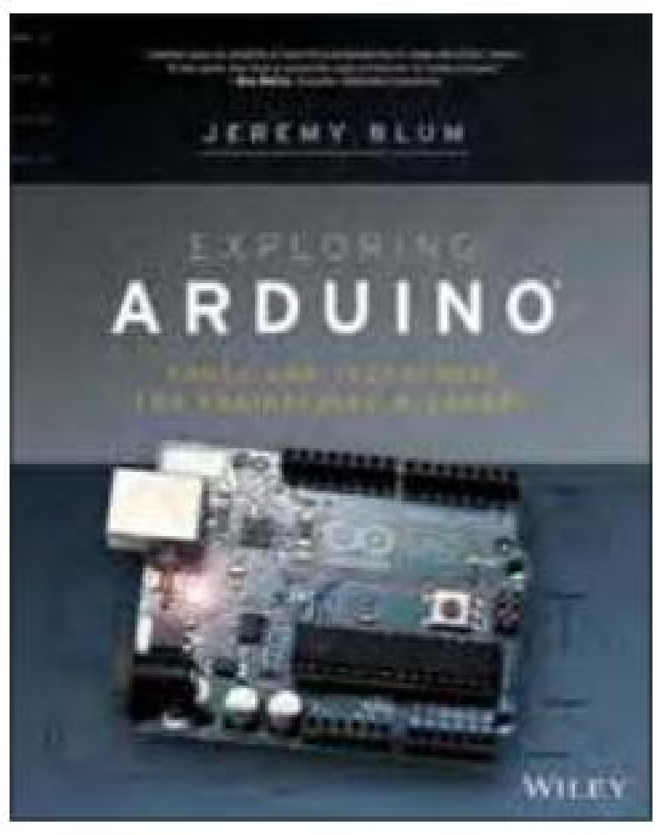

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Jeremy Blum

Arduino can take you anywhere. This book is the roadmap.

Exploring Arduino shows how to use the world's most popular microcontroller to create cool, practical, artistic and educational projects. Through lessons in electrical engineering, programming and human-computer interaction, this book walks you through specific, increasingly complex projects, all the while providing best practices that you can apply to your own projects once you've mastered these. You'll acquire valuable skills – and have a whole lot of fun.

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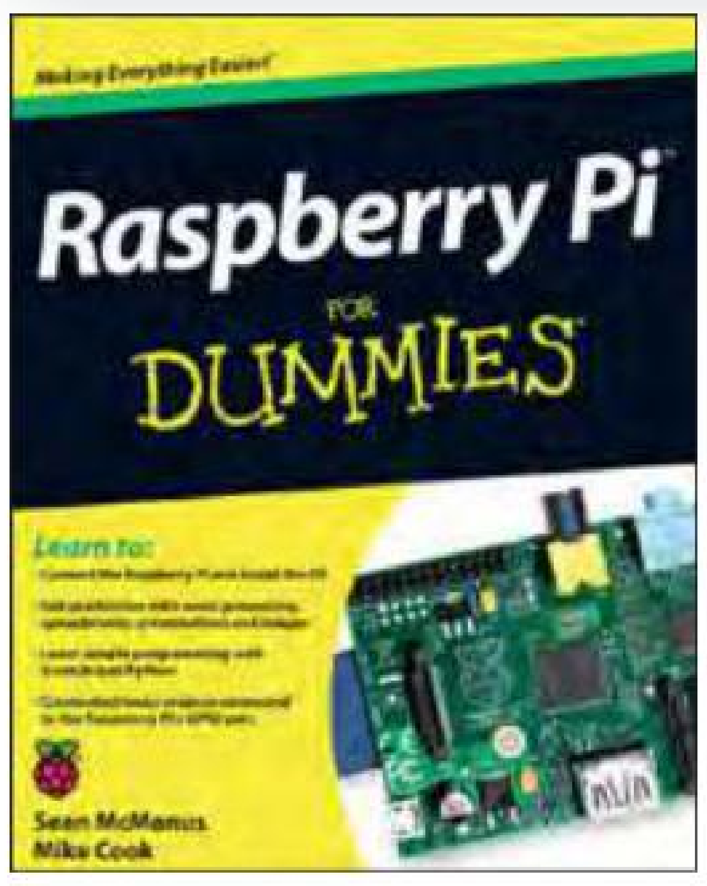

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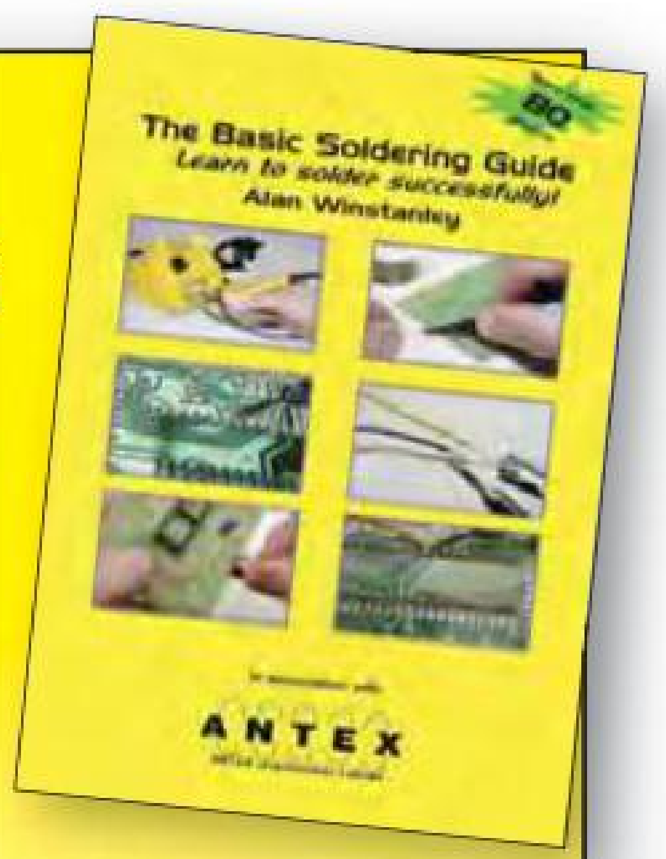

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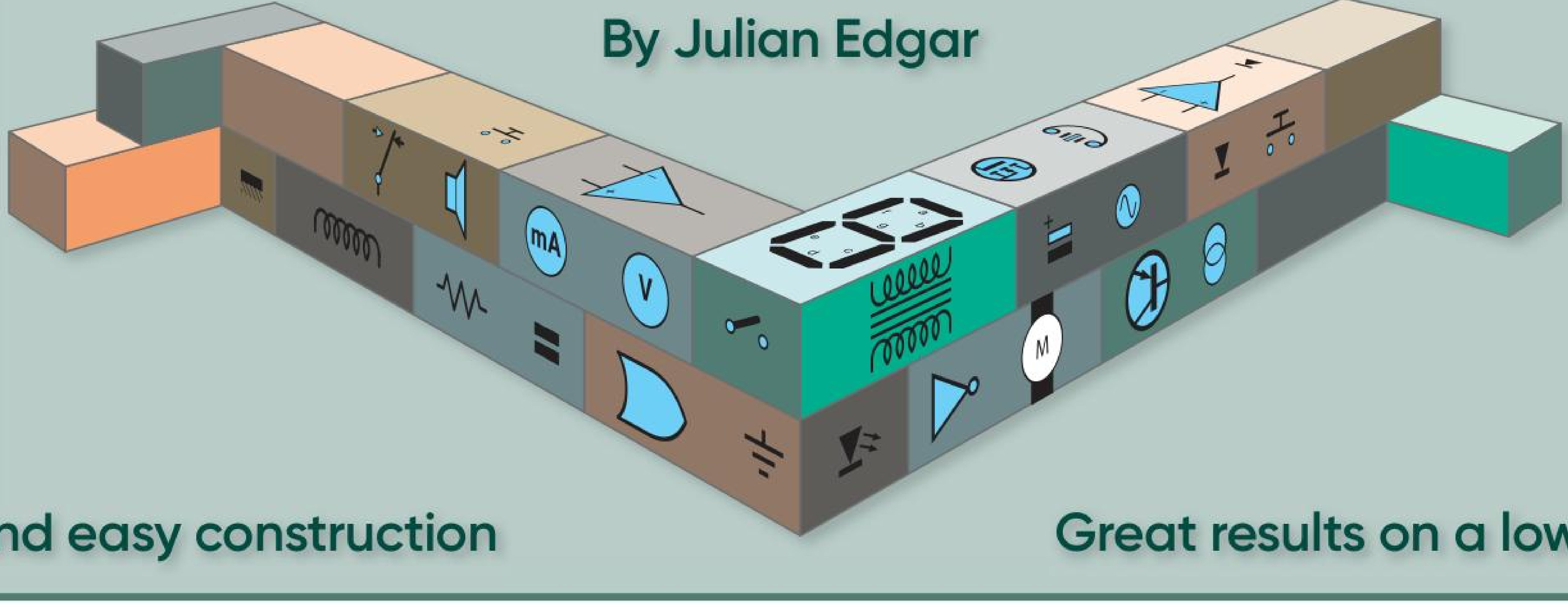
By Julian Edgar



Quick and easy construction

Great results on a low budget

World's best DIY car immobiliser

Let's think for a moment about someone stealing your car. If you have an older car – perhaps a classic – it's easy for a thief to steal it. These cars have no real protection except for an ignition lock – and that's easily bypassed and/or broken. You might feel that your car is much more secure if it runs electronic engine management and a smart key system – but think again. All the thief has to do in that case is steal your keys, and then they can just drive off in the car. But what if you have an expensive alarm and/or immobiliser, one that you've additionally fitted? Again, if the thief steals your keys they're laughing – they just disable the alarm in the way that you usually do (by pressing a button on the key fob) and away they go.

The car immobiliser we're presenting here won't stop a thief winching your car onto a flat-bed truck and driving off with it, but it is likely to considerably slow down any thief that is less determined. And – and here's the killer advantage – even if they steal your keys, it won't be of any advantage to them.

Circuit design

Let's take the circuit description one step at a time. The circuit uses two relays and a switch. Both relays have 12V coils. One relay is a low-current, double-pole double-throw (DPDT) design and the other is a single-pole single-throw (SPST) design – a conventional high current 12V car relay.

Let's look at Relay 1 first. It disables any circuit that the car needs to have working in order to start and run. On older cars it's easiest to break the power supply to the ignition coil. On more recent cars, disabling the fuel pump is a good approach. Relay 1 is shown in its unpowered state – note how the default position is that the car is disabled.

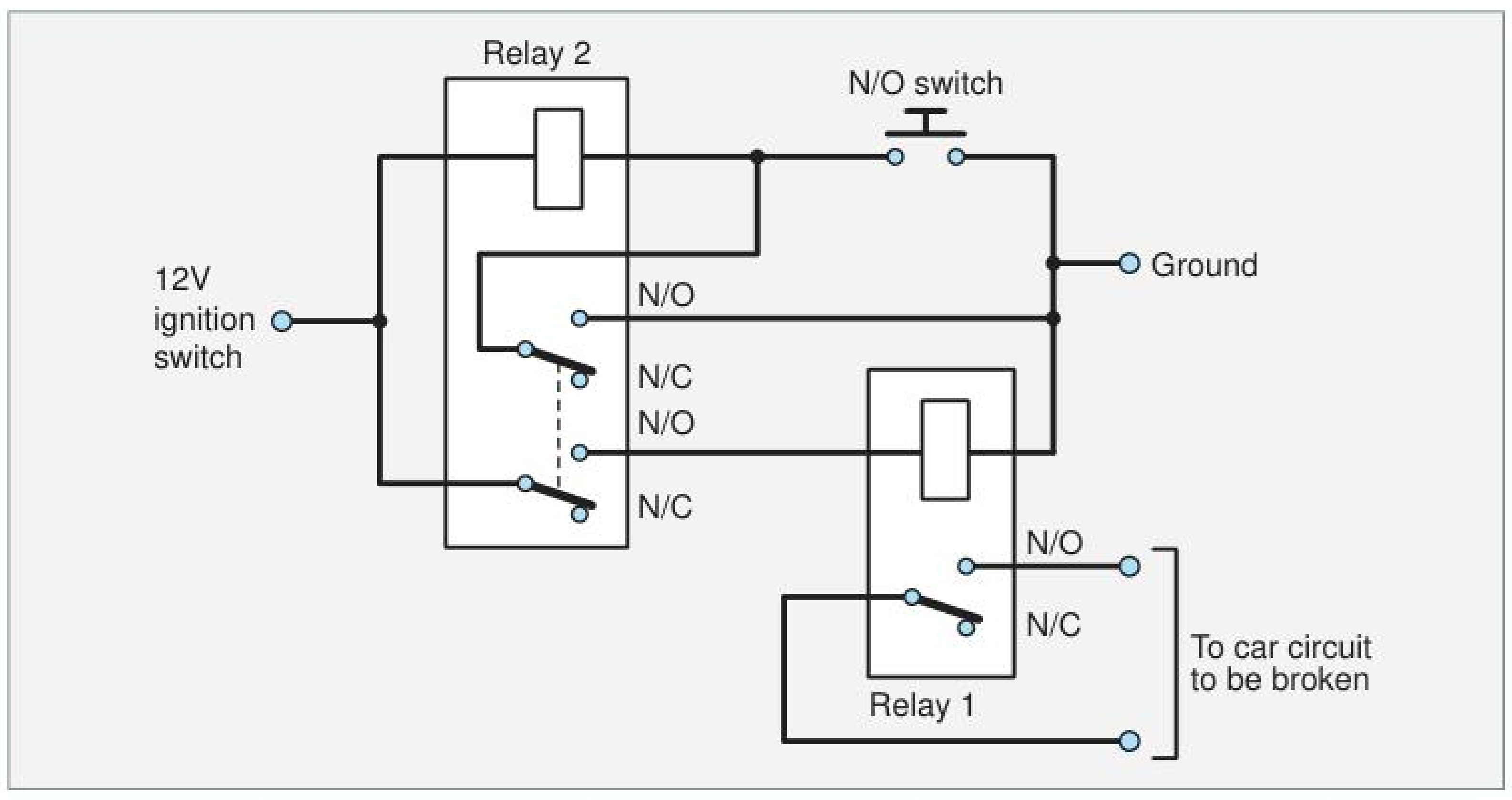


Fig.1. The immobiliser uses just two relays and a switch. Relay 1 disables a car circuit (eg, the ignition coil or fuel pump) while Relay 2 controls when the immobiliser operates. In operation, the N/O switch is momentarily closed which latches Relay 2, so feeding power to Relay 1 and allowing the car to operate. The trick is that the N/O switch is a hidden reed switch, triggered by swiping a magnet concealed in a dummy key fob. Without knowing the trick to disable the immobiliser, the car is disabled – even if the thief steals your keys.

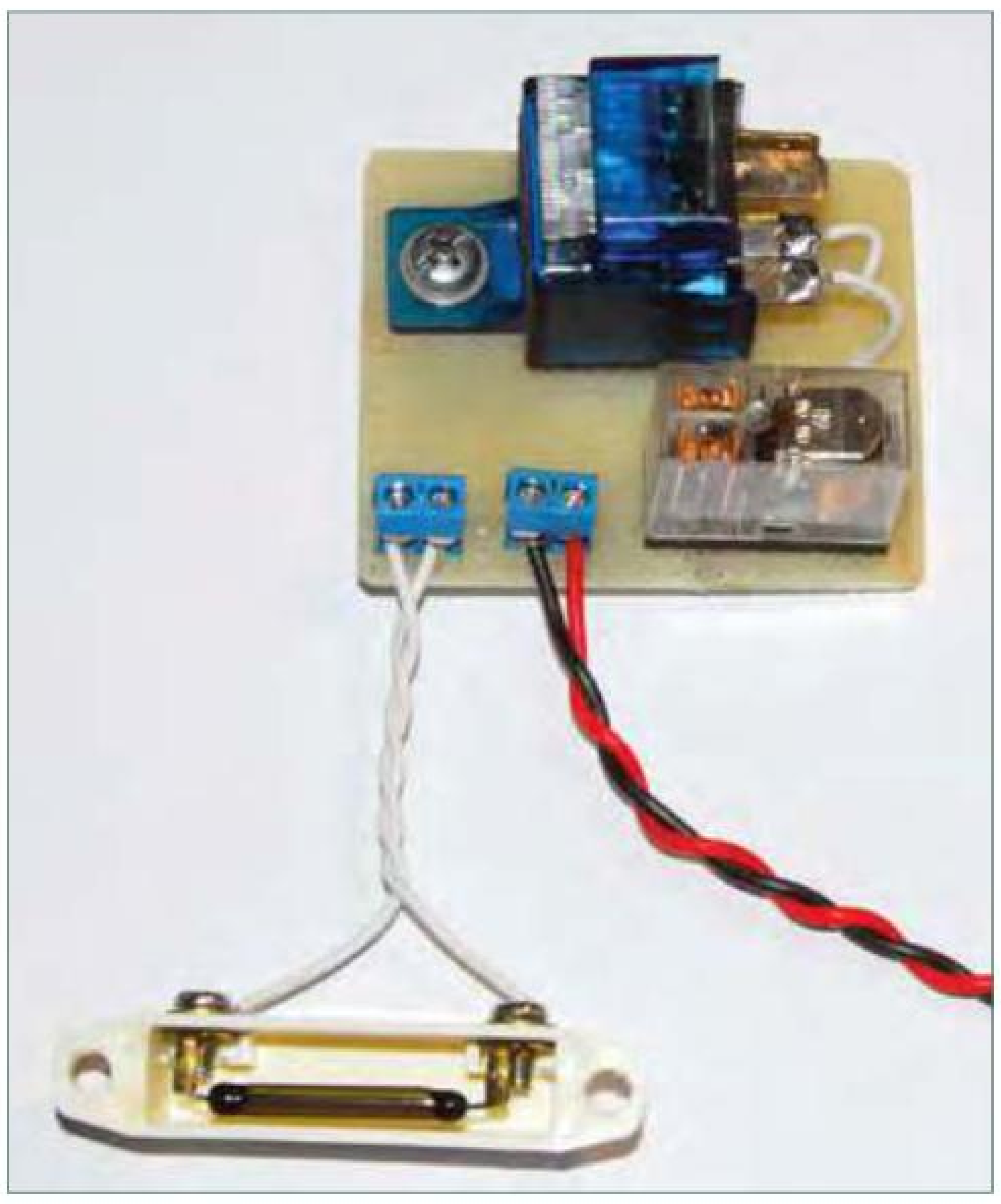


Fig.2. The system is simple and easily constructed on a piece of punched board. The top relay is a normal car relay, rated at the required current. This is the relay that disables the car. Here a security-type pre-packaged reed switch has been used, but a bare glass reed switch is even easier to conceal. Note that the car-disabling relay can be mounted anywhere (it doesn't need to be on this board) and the wires to the reed switch can be easily extended.

Relay 2 is used to control Relay 1. Relay 2 is powered from an ignition-switched 12V source. That is, a wire that has 12V on it only when the ignition is on and when the engine is cranking. When the normally open (N/O) switch is pressed, Relay 2's coil is energised and that pulls across the two sets of contacts. The upper contact causes the relay to stay energised, even when the switch is released. (That is, the relay is latched.) The latched Relay 2 feeds power to Relay 1's coil, so closing this relay and completing the car circuit that was otherwise broken. The car can then start and run.

To put this another way, until the N/O switch is momentarily closed, the car won't run. Now, here's the bit that makes this immobiliser unique. The N/O switch is actually a reed switch that is triggered momentarily by the passing of magnet close to it. The reed switch does not have to be visible – instead, it can be placed behind any plastic panel in the car's cabin.

Operation

So how does the system work in practice? When you drive the car and come

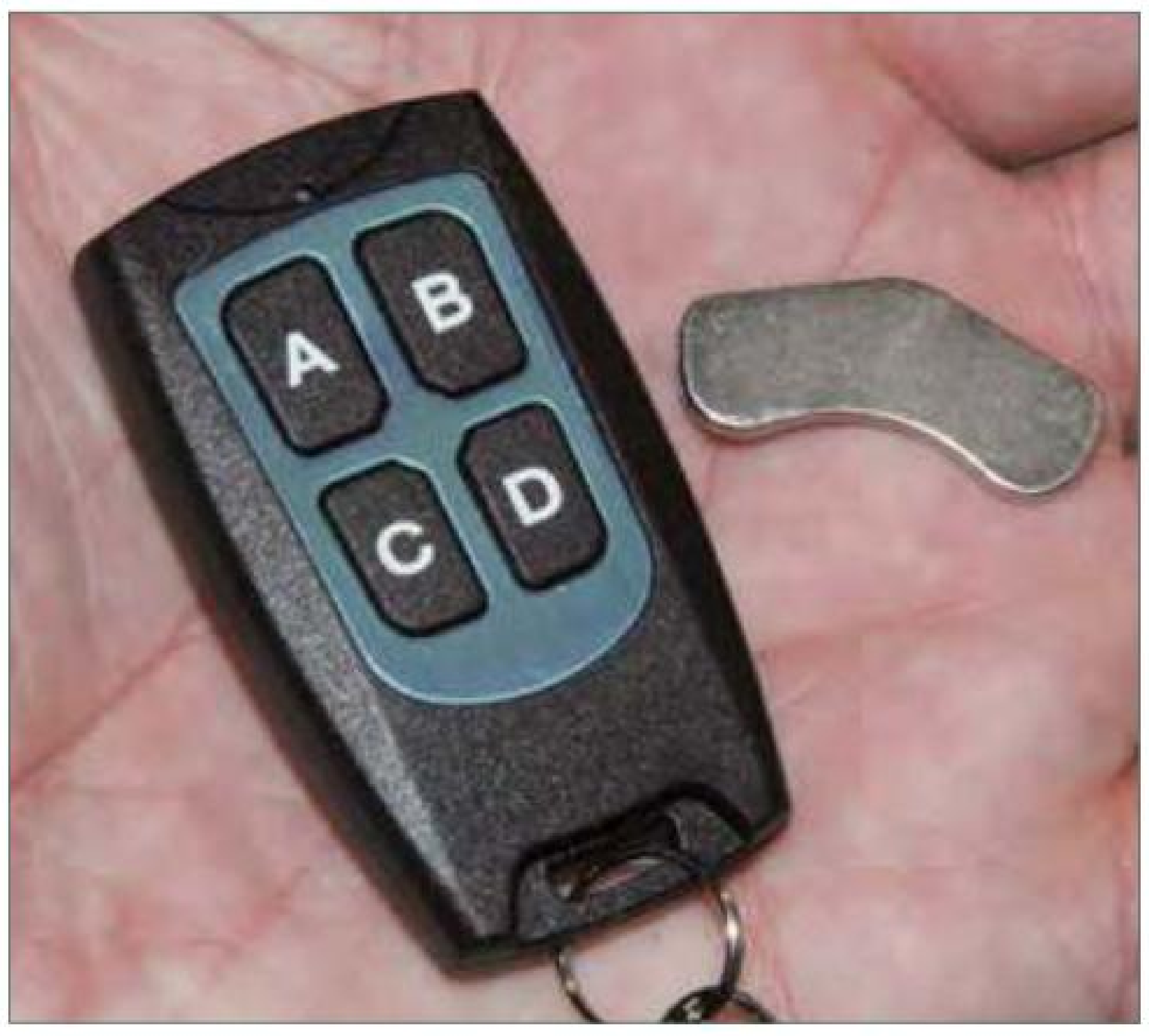


Fig.3. A small magnet (right) is concealed in a gutted key fob, and the key fob added to your existing keys or left in the car. When you get into the car, simply swipe the 'magnetic' key fob past the concealed reed switch to turn off the immobiliser. This magnet has been salvaged from an old computer hard drive.

to a halt, you switch off the ignition. This causes power to be cut to Relay 2, and therefore Relay 1, so disabling a starting circuit in the car. The car's immobiliser has therefore been activated without you having to do anything except switch off the car's ignition.

When you get back into the car, you turn on the ignition and then swipe a magnet past the hidden reed switch. This causes Relay 2 to latch and power Relay 1, allowing the car to be started.

Now, here's the second tricky bit. The small magnet can be hidden inside a gutted key fob transmitter! Furthermore, the motion of passing the key fob over a special spot inside the car can be done completely naturally. Even if the thief is observing you getting into your car, they won't suspect a thing! It won't help them if they steal your keys, because they won't know the trick. You can keep the 'magnetic' key fob somewhere handy in the car (just not near the reed switch!) or if you place the magnetic key fob on a short extension, keep it with your normal car keys. Remember, you need to turn on the ignition before swiping.

Note also that the power drain of the system when the car is off is zero. This makes the immobiliser suitable for cars that are not driven daily.

Making it

All the parts are readily available – in fact, you probably have some in your scrap box. If you need to buy new, check eBay – the lot shouldn't cost you more than £10. Ensure that the reed switch is a N/O design, and if you buy a bare one, treat it carefully as the glass envelope can easily crack if you bend the leads close to it.

Make sure you ascertain the N/O and N/C (normally closed) terminals on the DPDT relay (you could use a DPST relay, but DPDT designs are more common). Build the 'latching' part of the circuit first, apply power and ensure that when the switch contacts are momentarily bridged, the relay stays pulled-in. The rest of the circuit should be straightforward to build.

Note that it's easy to add extra components. For example, a green 12V LED wired across Relay 1's coil will show when the immobiliser circuit has been disabled and you're good to go. The bottom unused contact on Relay 2 can be used to show when the immobiliser is active – just connect a 12V flashing LED between this terminal and ground. (Note though, there will then be a current draw when the car is off.) This flashing LED can also be used as a driver reminder to disable the immobiliser.

So there you have it! An immobiliser that's perfect for cars, motorcycles and agricultural equipment – and it's simple, cheap and very effective.

Next month

In the September issue it's 'tick-tock', as we look at three different clock and timer modules.

Teach-In 8 CD-ROM
Exploring the Arduino

This CD-ROM version of the exciting and popular *Teach-In 8* series has been designed for electronics enthusiasts who want to get to grips with the inexpensive, immensely popular Arduino microcontroller, as well as coding enthusiasts who want to explore hardware and interfacing. *Teach-In 8* provides a one-stop source of ideas and practical information.

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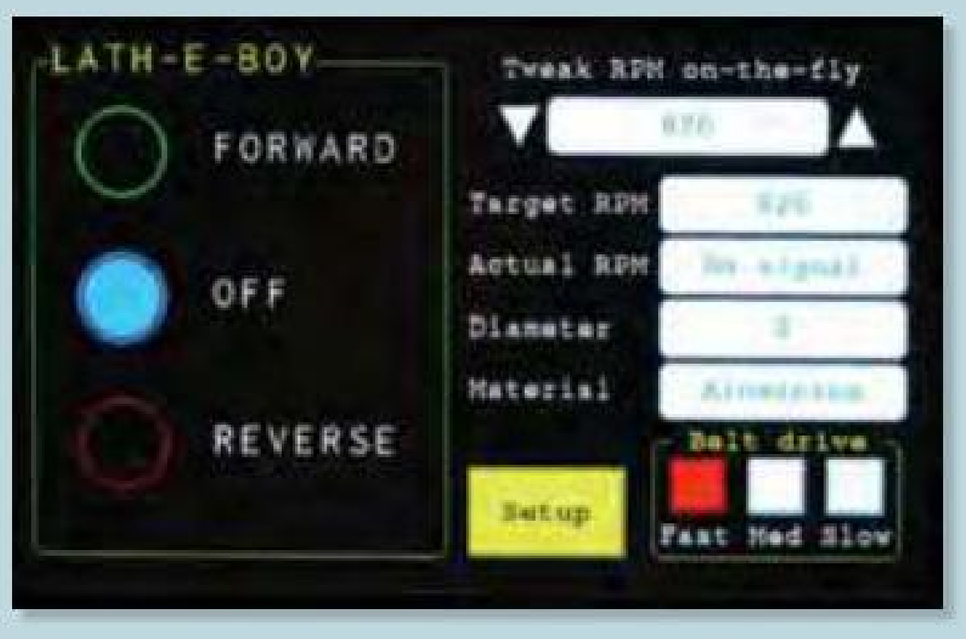

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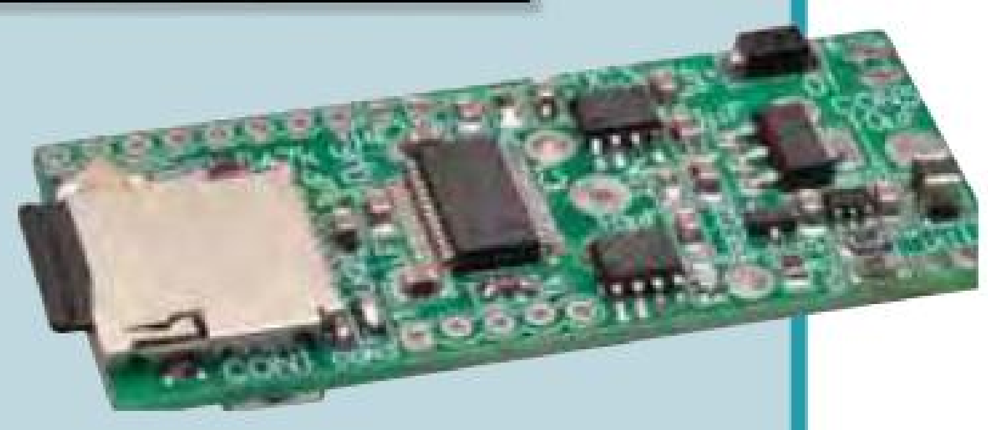

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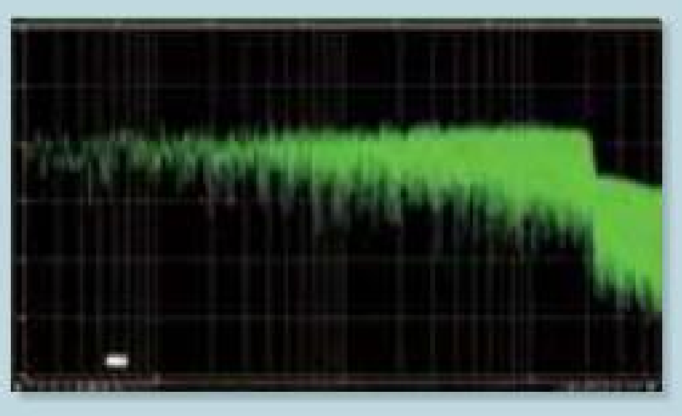

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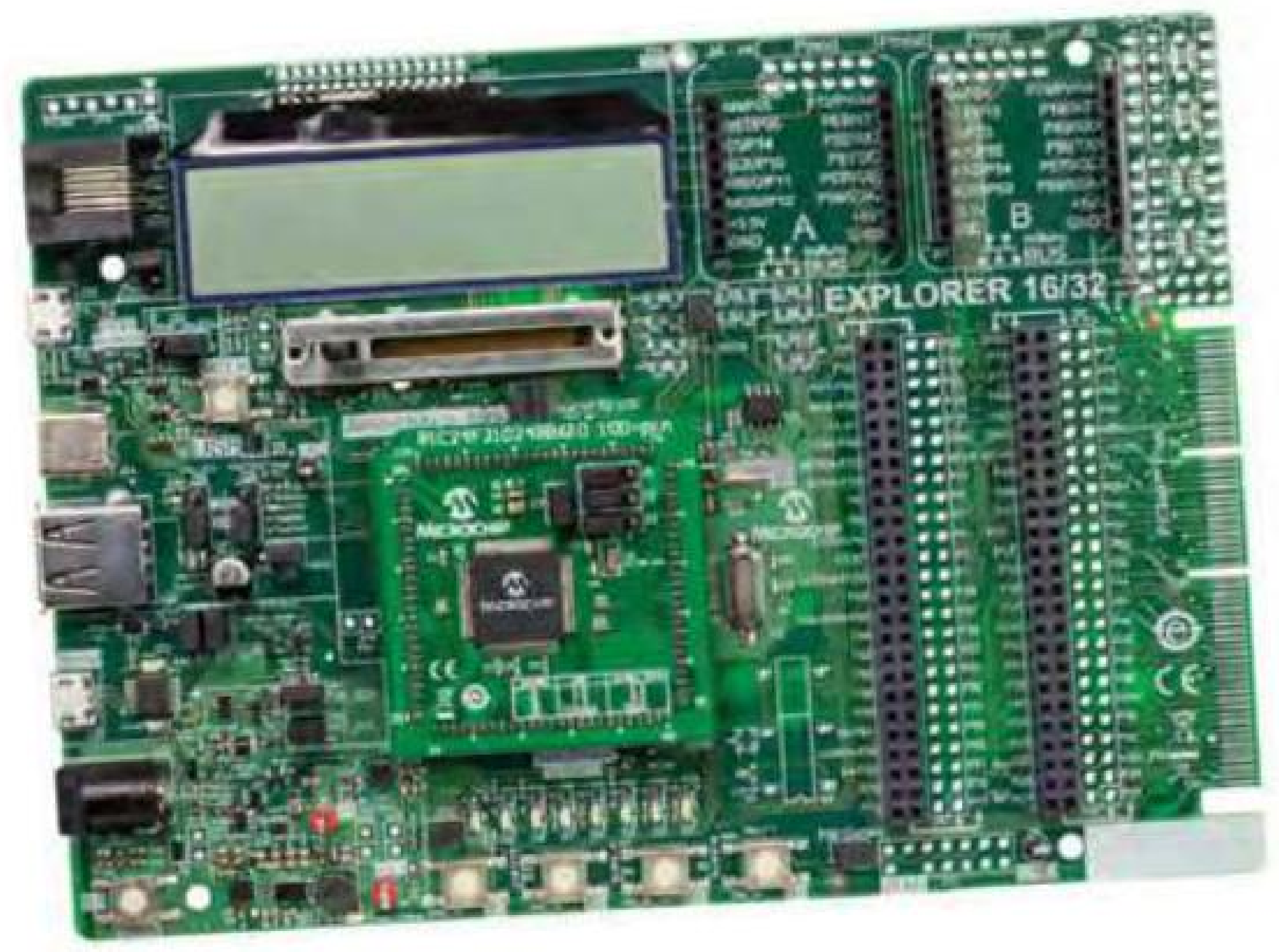
Development Tool of the Month!

Explorer 16/32 Development Kit



Part Number
DM240001-3

Overview:

The Explorer 16/32 Development Kit is a flexible, convenient and ready to start development, demonstration and testing platform for 16-bit PIC24 MCUs, dsPIC® DSCs and 32-bit PIC32 MCUs from Microchip Technology. It features all the necessary hardware to begin developing and debugging a complete embedded application. The board accepts Processor Plug-In Modules (PIM) designed for the Explorer 16 or Explorer 16/32 development board for easy device swapping. In addition to the hardware features provided by the board, hardware expansion is possible through the use of PICtail™ Plus daughter cards and mikroBUS™ accessory boards. Coupled with the integrated PICkit™-On-Board (PKOB), MPLAB ICD 3 In-Circuit Debugger or MPLAB REAL ICE™ real-time emulation and debug facilities enable faster evaluation and prototyping of application.

The development kit comes with Explorer 16/32 main development board, PIC24FJ1024GB610 PIM (MA240023), USB A to micro-B cable, and USB A to Type-C Cable. For out of the box experience, Explorer 16/32 Development Kit is the right choice that comes with all the necessary components to get started with the evaluation and prototyping right away!

Order Your Explorer 16/32 Development Kit Today!

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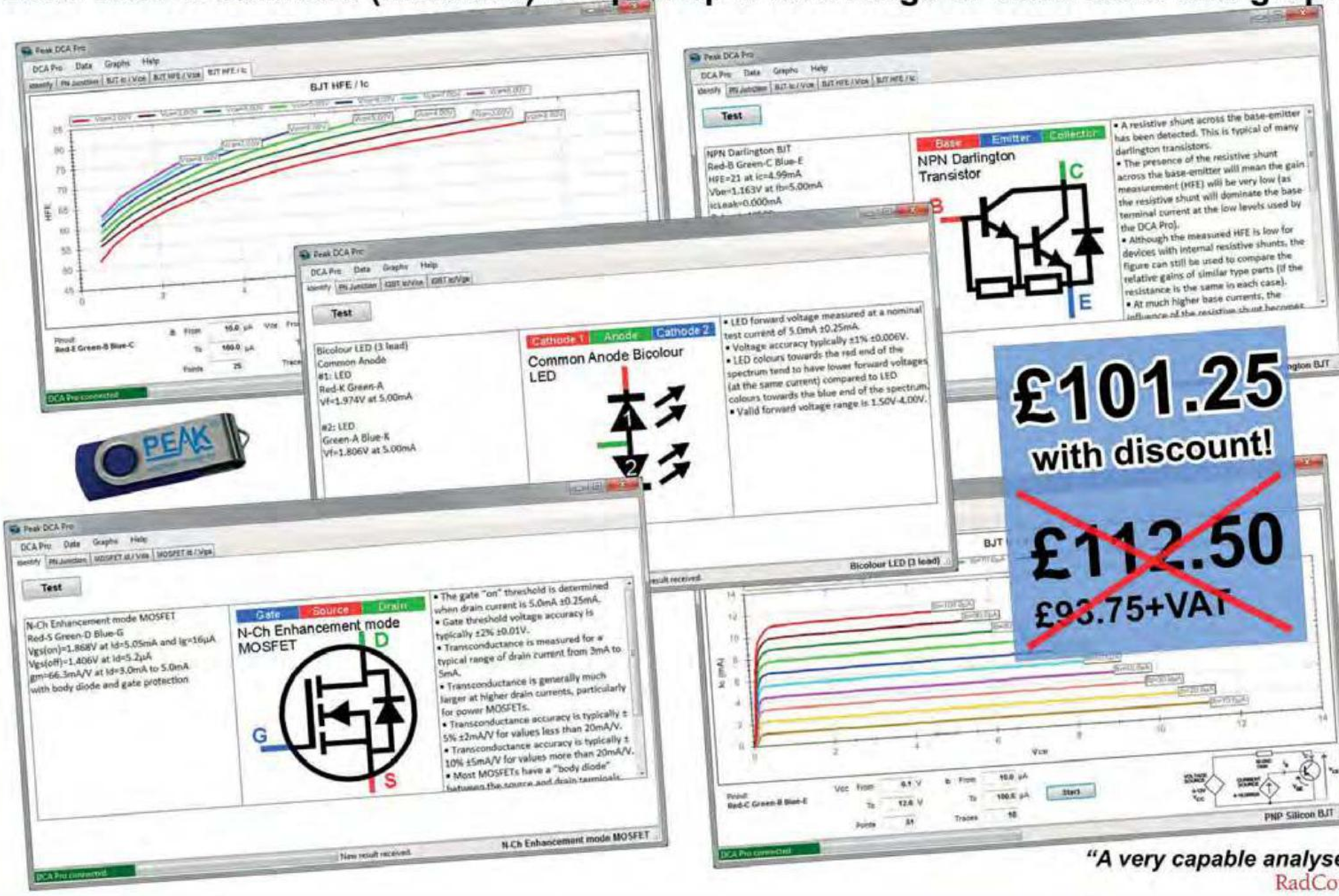
Load the PC software (included) to open up a vast range of extra tests and graphs.


Peak DCA Pro
DCA Pro
Data
Graphs
Help
Identify
PN Junction
Test
BJT HFE / Ic
Base
Emitter
Collector
NPN Darlington Transistor
Cathode 1
Anode
Cathode 2
Common Anode Bicolour LED
Gate
Source
Drain
N-Ch Enhancement mode MOSFET
DCA Pro connected
New result received
Bicolour LED (3 lead)
N-Ch Enhancement mode MOSFET
PNP Silicon BJT
PEAK

NPN Darlington BJT
Red-B Green-C Blue-E
HFE=21 at Ic=4.99mA
Vbe=1.163V at Ib=5.00mA
IcLeak=0.000mA

- A resistive shunt across the base-emitter has been detected. This is typical of many darlington transistors.
- The presence of the resistive shunt across the base-emitter will mean the gain measurement (HFE) will be very low (as the resistive shunt will dominate the base terminal current at the low levels used by the DCA Pro).
- Although the measured HFE is low for devices with internal resistive shunts, the figure can still be used to compare the relative gains of similar type parts (if the resistance is the same in each case).
- At much higher base currents, the

Bicolour LED (3 lead)
Common Anode
#1: LED
Red-K Green-A
Vf=1.974V at 5.00mA

#2: LED
Green-A Blue-K
Vf=1.806V at 5.00mA

- LED forward voltage measured at a nominal test current of 5.0mA ±0.25mA.
- Voltage accuracy typically ±1% ±0.006V.
- LED colours towards the red end of the spectrum tend to have lower forward voltages (at the same current) compared to LED colours towards the blue end of the spectrum.
- Valid forward voltage range is 1.50V-4.00V.

N-Ch Enhancement mode MOSFET
Red-S Green-D Blue-G
Vgs(on)=1.868V at Id=5.05mA and Ig=16µA
Vgs(off)=1.406V at Id=5.2µA
gm=66.3mA/V at Id=3.0mA to 5.0mA
with body diode and gate protection

- The gate "on" threshold is determined when drain current is 5.0mA ±0.25mA.
- Gate threshold voltage accuracy is typically ±2% ±0.01V.
- Transconductance is measured for a typical range of drain current from 3mA to 5mA.
- Transconductance is generally much larger at higher drain currents, particularly for power MOSFETs.
- Transconductance accuracy is typically ± 5% ±2mA/V for values less than 20mA/V.
- Transconductance accuracy is typically ± 10% ±5mA/V for values more than 20mA/V.
- Most MOSFETs have a "body diode"

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